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EMULSIFICATION TEST FOR MARINE ENGINE OILS

THE Miscellaneous Tests of Lubricants Panel of IP Standardization Sub-Committee No. 6 has completed a programme of correlation tests with a view to establishing a standard procedure for determining the emulsifying properties of marine engine lubricating oils.

A draft method of test has been agreed, but the demand for such a test is insufficient to warrant its being put forward as an IP Standard. It is, therefore, published here for the benefit of those who may be interested.

EMULSIFICATION—MARINE ENGINE OILS

SCOPE

1. This method determines the emulsification tendency of marine engine lubricating oils.

OUTLINE OF METHOD

2. Equal volumes of the sample and of an emulsifying liquid are mixed by stirring with a rotating paddle. The resulting emulsion is then stood for a specified time and inspected for separation.

APPARATUS

3. (*a*) *Graduated Cylinder*—of 100-ml capacity, graduated in 1- and 10-ml divisions, approx 25 mm in height and 27 $\pm$ 0·5 mm internal dia.

(*b*) *Paddle*—of copper or other non-corrodible metal, 4·75 to 4·76 inches (120·65 to 120·9 mm) long, 0·75 to 0·76 inch (19·05 to 19·3 mm) wide, and 0·0625 to 0·0725 inch (1·59 to 1·84 mm) thick.

(*c*) *Drive Unit*—a variable speed motor capable of rotating the paddle around its longitudinal axis at speeds up to 1500 r.p.m., and constructed so that the paddle can be lifted vertically from the cylinder. The paddle holder shall be designed so that the paddle does not foul the cylinder sides during rotation.

(*d*) *Tachometer*—to indicate speed of rotation.

(*e*) *Water Bath*—capable of maintaining the sample at the test temperature and of sufficient depth to ensure that the whole sample is below the level of the liquid in the bath throughout the test.

(*f*) *Thermometer*—conforming to the specification IP 3, F or C.

MATERIALS

4. *Emulsifying Liquids*—distilled water, or a 1% solution of sodium chloride in distilled water.

PREPARATION OF APPARATUS

5. (*a*) Clean the graduated cylinder to remove all traces of oily material and dry by heating in an oven.

(*b*) Wash the paddle with IP petroleum spirit to remove all traces of oil, rinse with distilled water, dry, and place in position in the paddle holder.

(*c*) Heat the water bath to the test temperature (usually 130° F or 54·5° C) and maintain at that temperature $\pm$1° F (0·5° C).

PROCEDURE

6. Place 40 ml of the emulsifying liquid in the clean graduated cylinder, add 40 ml of the sample, and place the cylinder in the water bath. Lower the paddle into the cylinder so that it is concentric with the cylinder and the distance between the bottom of the paddle and the bottom of the cylinder is 0·25 inch (6·35 mm).

When the contents of the cylinder reach the test temperature, commence rotation of the paddle, slowly at first and increasing to 1500 r.p.m. in 10 $\pm$ 2 sec. Continue stirring at this rate for 5 min (Note 1).

NOTE 1: It may be necessary to adjust the motor speed to maintain 1500 r.p.m. throughout the stirring period.

Stop the paddle, raise it from the cylinder, and wipe clean with a rubber policeman, returning to the cylinder as much emulsion as possible.

Allow the cylinder to stand for the specified time and then inspect.

ERRATUM

NOTE ON THE WEAK MIXTURE KNOCK-RATING OF AVIATION FUELS ABOVE 100 OCTANE NUMBER

Page 241. *The last line of Section* (4) (i) *should read:*

"0·25 ml for 2·5 ml or more per USG; or."

TEMPERATURES AND THERMAL CONDUCTIVITY OF THE GROUND ALONG THE ALIGNMENT OF THE 30-INCH PIPELINE KIRKUK–BANIAS IN RELATION TO OIL TEMPERATURES *

By T. B. MURRAY† and W. C. R. WHALLEY†

SUMMARY

Soil temperatures and thermal conductivities were determined at fifty sites along the 556-mile route of the 30-inch pipeline from Kirkuk, N. Iraq, to Banias, Syria. This information was required for oil temperature prediction. Thermal conductivities were derived from the decrement and lag of the annual temperature waves at 2, 4½, and 6½ feet, obtained by frequent observation of thermometers in closed asbestos tubes. The necessary soil densities and specific heats were found by laboratory measurements on samples. In the method of mixtures for specific heats aluminium pellets were used as a standard, and inclined rotating calorimeters to obtain effective mixing of the two components. Some oil temperature predictions are compared with the corresponding observed values.

Recorded results include :

(*a*) thermal conductivities, specific heats, densities, and monthly average soil temperatures by locations and depths;

(*b*) reproductions of temperature waves by locations and depths.

INTRODUCTION

THE calculation of oil temperatures in a buried pipeline is the subject of a monograph.[1] The information required for this calculation may be summarized as :

(*a*) pipe diameter;

(*b*) throughput;

(*c*) frictional resistance to flow; *i.e.* frictional heat generated by the flowing oil;

(*d*) initial oil temperature;

(*e*) ground temperature at pipe depth but remote from pipe;

(*f*) thermal conductivity of ground surrounding the pipe.

The information under headings (*a*), (*b*), (*c*), and (*d*) would be available in any particular case from general design data. This does not apply to ground temperature and thermal conductivity, information on which is usually sparse or entirely lacking.

In the case of the 30-inch pipeline from Kirkuk to Banias some work on thermal conductivity had been carried out by Brummage [2] in 1948. This investigation, however, was restricted to determining thermal conductivities over three widely separated sections, totalling 40 miles of the alignment in Iraq, and did not include information on soil temperatures at differing seasons and depths.

When the original 12-inch lines from Kirkuk to Haifa and Tripoli were under consideration in 1931 calculations of oil temperatures [1] were made on the slender information available at that time. These calculations are to be found in the monograph in the " Science of Petroleum."

Accurate oil temperature prediction assumes greater importance as pipe diameters are increased. As a first approximation, the tonnage throughput of a line pumping Middle East crude at constant gauge pressure may be taken to increase by 1 per cent for every 10° F rise in oil temperature. It is evident that the importance of temperature effects is far greater in a 30-inch pipeline carrying 50,000 tons per day than in a 12-inch pipeline pumping 7000 tons. In pipelines of increasing diameter the rate at which heat is generated by friction increases more rapidly than the rate at which it is lost to the ground. The quantity of oil flowing in the pipeline, and hence the amount of heat generated by friction, is nearly proportional to the cube of the diameter for equal hydraulic gradients. On the other

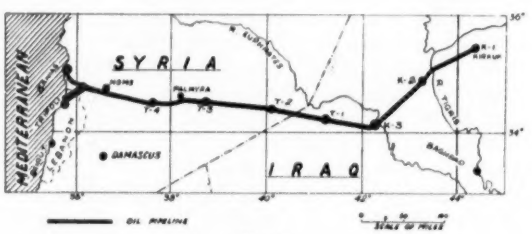


FIG 1

hand, the rate of heat transfer to the ground is found to be proportional not to the diameter but more nearly to its square root. In the result, oil temperatures in long pipelines of large diameter tend to be considerably higher than ground temperatures, whereas in smaller diameter pipelines the difference is not so marked.

With a view to improving the prediction of pipeline temperatures and throughputs an extensive investigation of ground temperatures and thermal conductivities was undertaken over the whole alignment of the 30-inch pipeline between Kirkuk and Banias. A sketch map of the area is shown in Fig 1. The length

* MS received 22 February 1954.

† Iraq Petroleum Co. Ltd., Tripoli.

of the pipeline is 556 miles. The profile of the alignment and the rainfall distribution are shown in Fig 2.

The method adopted in this investigation was that of determining the temperature wave at three different depths in the ground. These depths were arranged to include ground above and below the level of the pipe. Fifty different sites were employed, mainly in the open desert, and at each site soil temperatures were taken at three depths, namely 2 ft, 4½ ft, and 6½ ft. The centre line of the 30-inch pipe is at 3¼ ft, and thus the effective thermal conductivity of the ground at pipe depths, and above and below it, could be calculated for each site. Reduced tracings of the temperature waves are shown at the end of this paper.

The method of calculating the thermal conductivity of the soil from the temperature wave and its subsequent use for oil temperature predictions is described in the monograph of Beale *et al.*[1] A more

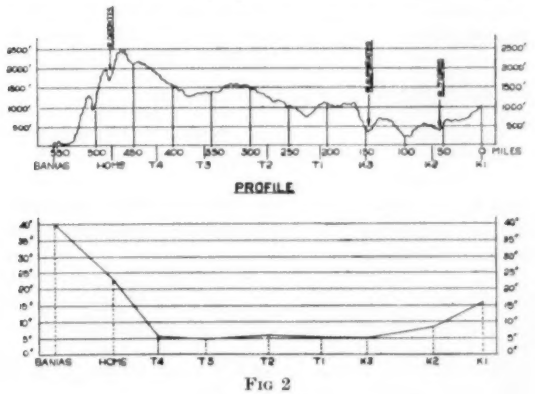


FIG 2

Twenty-year averages (except Banias)

extensive treatment of the heat wave is given by Ingersoll and Zobell.[3] From the characteristics of the respective temperature waves at different depths the thermal diffusivity is derived. In order to obtain the thermal conductivity from the diffusivity it is necessary to know the specific heat and density of the corresponding layer of soil. These properties were determined by experiments in the laboratory on specimens taken from the various sites.

The results are tabulated as follows :

Table II. Full Table of Soil Thermal Conductivities by Locations and Depths with Densities and Specific Heats.

Table III. Concise Table of Weighted Mean Conductivities by Pipeline Sections.

Table IV. Concise Table of Monthly Average Soil Temperatures by Depths.

The tabulated figures show clearly that thermal conductivity increases with depth consequent on the presence of rock in most areas.

Some examples of the results obtained by applying the foregoing information to oil temperature predictions are shown in Fig 7. This shows predicted and some observed temperatures between K-3 pump station and the Banias terminal. The distance involved is 406 miles. The pipeline route from K-3 to T-4 lies solely in desert country. The section between T-4 and Banias, however, contains extensive flooded areas and numerous streams during the rainy season. Accordingly, an empirical adjustment of −5° F has been made to the Banias temperatures for the winter season and −3° F for spring.

The observed figures for the intermediate stations are not complete. Nevertheless, an examination of Fig 6 shows that fair agreement is obtained between predicted and observed figures. Predicted temperatures at T-4 tend to lie between 1° and 4° F high.

In some few instances it has been possible to obtain values for soil conductivities from the alternative method of oil temperature measurement in the pipeline. These are shown in Table V. Fair agreement is obtained in this limited comparison.

SYMBOLS EMPLOYED

The symbols used throughout this paper are defined or explained below. The meaning of symbols used with special suffixes not explicitly defined should be obvious, *e.g.* T_x is given as the soil temperature at depth x, so T_6 is the temperature at a depth of 6 ft. Engineering units are used consistently.

A = coefficient of heat transfer from unit length of pipe to soil, B.T.U/ft run/hr/° F;

$$= \frac{4\pi k}{\ln\left(\frac{h+\sqrt{h^2-r^2}}{h-\sqrt{h^2-r^2}}\right)} \doteq \frac{2\pi k}{\ln\left(\frac{2h}{r}\right)} \text{ approximately}$$

c = thermal capacity (numerically equal to specific heat value), B.T.U/lb/° F;
c_0 = thermal capacity of oil, B.T.U/lb/° F;
e = 2·71828 . . . = base of natural logarithms;
h = depth of pipe centre, ft;
H = frictional heat developed in unit length of pipe, B.T.U/ft run/hr;
k = thermal conductivity, B.T.U/sq. ft/hr/° F/ft;
ln = natural logarithm, *i.e.* logarithm to base e;
L = length of subsection of pipeline, ft;
m = mass throughput of oil, lb/hr;
n = number of observations;
r = external radius of pipe, ft;
R = ratio of annual temperature ranges or amplitudes at different depths;
t = time, hr;
t_l = lag of temperature wave, hr;
T = temperature, ° F;
T_h = temperature of ground remote from pipe at depth h of pipe centre, ° F;
T_0 = temperature of oil entering the pipe, ° F;
$\hat{T}_0$ = amplitude of temperature wave;
$\hat{T}_x$ = amplitude of temperature wave in soil at depth x = half temperature range, ° F;
T_x = soil temperature at depth x and time T.
T_L = temperature of oil at distance L along line, ° F;
x = difference of depths, ft;
α = thermal diffusivity

$$= \frac{\text{thermal conductivity}}{\text{thermal capacity} \times \text{density}} = \frac{k}{c\rho}, \text{ sq. ft/hr;}$$

ρ = density;
ω = angular velocity of temperature wave

$$= \frac{2\pi}{\text{period of temperature wave in hours}}, \text{ radians/hr.}$$

TERMS USED

The annual temperature *range* at any depth is the difference between the maximum and minimum temperature (Fig 3).

The *amplitude* of the temperature wave is half the range.

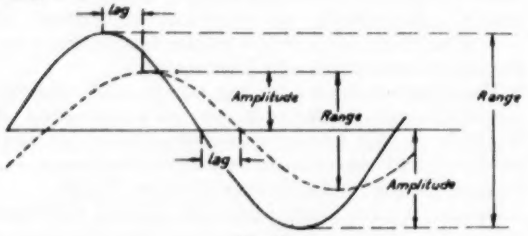


FIG 3

The *lag* is the time required for a given phase of the heat wave to pass from one depth to another.

If a 1-ft cube of soil is considered, then :

Volumetric heat capacity is the number of B.T.U. required to raise the temperature of the cube by 1° F = thermal capacity × density.

Thermal conductivity is the number of B.T.U/hr flowing across the cube when a temperature difference of 1° F is maintained across the two opposing faces.

Thermal diffusivity may be considered as rate of temperature change of the whole cube (° F/hr) when heat flows across the cube under the effect of 1° F temperature difference across two opposing faces.

OUTLINE OF THEORY OF HEAT WAVE

It is a basic assumption in the treatment of soil temperatures that there is a periodic heat flow into and out of the earth. It follows from this that the corresponding temperature curves must have a simple or compound sine form.

The fundamental equation is :

$$T_x = \widehat{T}_0 e^{-x\sqrt{\frac{\omega}{2\alpha}}} \sin\left\{\omega t - x\sqrt{\frac{\omega}{2\alpha}}\right\} \quad . \quad (1)$$

This equation is derived from the Fourier conduction equation, assuming

(*a*) Sinusoidal temperature variation at the bounding plane, *i.e.*

$$T_0 = \widehat{T}_0 \sin \omega t \quad . \quad . \quad . \quad (2)$$

In the case considered the bounding plane is either at the earth's surface or parallel to it.

(*b*) An isotropic medium, *i.e.* a soil with uniform properties in all directions, of diffusivity α.

Equation (1) gives the temperature at any depth and time. The factor $e^{-x\sqrt{\frac{\omega}{2\alpha}}}$ measures the decrease in amplitude with depth, while the expression $x\sqrt{\frac{\omega}{2\alpha}}$ in the sine term represents the corresponding phase change, and is therefore a measure of the lag in equation (1). The sine term is unity at the maximum temperature in the heat wave when, from equation (1),

$$\text{amplitude } \widehat{T}_x = \widehat{T}_0 e^{-x\sqrt{\frac{\omega}{2\alpha}}} = \tfrac{1}{2} \text{ range} \quad (3)$$

Hence if the annual temperature ranges at two depths are known, the diffusivity of the intervening soil layers can be calculated without knowledge of the surface temperature.

Alternatively, equation (1) shows that the temperature at any depth will be a maximum when

$$\sin\left\{\omega t - x\sqrt{\frac{\omega}{2\alpha}}\right\} = 1,$$

i.e. when

$$\left\{\omega t - x\sqrt{\frac{\omega}{2\alpha}}\right\} = \frac{\pi}{2}$$

(or any other coterminal angle), giving

$$\omega t = \frac{\pi}{2} + x\sqrt{\frac{\omega}{2\alpha}} \quad . \quad . \quad . \quad (4)$$

The lag t_1 between the occurrence of the maximum at the surface or any depth and at any other depth distant x is therefore given by :

$$t_1 = x\sqrt{\frac{\omega}{2\alpha}} \text{ or } \alpha = \frac{1}{2\omega}\left(\frac{x}{t_1}\right)^2 \quad . \quad (5)$$

The same reasoning holds if the minimum, zero, or any other phase is considered (see Fig 2). If the lag of the heat wave at any two depths is known, the diffusivity can therefore be calculated from equation (5).

By definition,

$$\text{diffusivity} = \frac{\text{conductivity}}{\text{volumetric heat capacity}}$$

Therefore, if the specific heat and density of the soil are known, the conductivity can be derived from the diffusivity already calculated by one of the alternative methods given above.

In a detailed account of the theory of this subject,[3] the derivation of equation (1) from Fourier's Conduction Equation is given. The application of the theory to calculation of oil temperatures in buried pipelines is the subject of a monograph.[1]

In practice, the ideal conditions assumed in the derivation of the fundamental equation are only partially fulfilled. The necessary assumptions may be restated in the particular form required for this investigation.

(*a*) The annual temperature change at the earth's surface is a simple periodic function, *i.e.* it varies sinusoidally.

(*b*) The thermal diffusivity of the soil is constant over the period of test, *i.e.* for at least one annual cycle.

(*c*) The heat flow is up or down only, *i.e.* normal to the surface. (With a plane surface, this assumption is unnecessary if (*b*) holds.)

The authorities are agreed that surface temperatures vary approximately sinusoidally over an annual period. In Middle East conditions the absence of cloud and rain in summer leads to a particularly close approximation to sine form for the upper portion of the temperature curve. In winter the agreement is generally less good, but nevertheless it appears that a fair approximation to the sine wave is obtained.

The present results show that the diffusivity usually varies considerably with depth. In fact, at many locations the type or condition of soil can be seen to change with depth, often to a marked degree. For example, there might be 3 ft of soil cover over solid limestone. Soil strata, however, were usually found to be locally quite uniform in the horizontal plane. The heat flow therefore must still be in one direction only. Accordingly, the diffusivity calculated from the annual temperature ranges at two depths may be considered as the effective diffusivity of the intervening soil layer, and similarly for diffusivity calculated from the lag of the heat wave.

The necessary assumptions therefore appear to be justified for our purpose. In this present investigation temperature curves were obtained for three different depths at each site. Each curve includes at least one-and-a-half annual cycles. From each curve annual temperature ranges were derived for the depth in question. Hence by taking the depths in pairs three corresponding values of diffusivity were obtained for the intervening layers.

In deriving the annual range the mean of the successive periods of 12 months was taken from the 18-month record. Thus, an average for two seasons was obtained.

Taking two depths, *e.g.* a and b, it is convenient to take x as their difference and consider the lesser depth a as the new boundary or surface.

Equation (3) then becomes :

$$\widehat{2T_b} = \widehat{2T_a} e^{-x\sqrt{\frac{\omega}{2\alpha}}}$$

or
$$R = \frac{\widehat{2T_a}}{\widehat{2T_b}} = e^{x\sqrt{\frac{\omega}{2\alpha}}} \quad (R > 1) \qquad . \quad (6)$$

quation (6) may also be written as

$$\ln R = x\sqrt{\frac{\omega}{2\alpha}}$$

where ln signifies the natural logarithm

or
$$(\ln R)^2 = x^2 \frac{\omega}{2\alpha}$$

Now $\frac{\omega}{2} = \frac{\pi}{8760} = 0{\cdot}0003586$ radian/hr, since the period of the heat wave is one year or 8760 hr. This leads to the convenient form :

$$\alpha = 0{\cdot}0003586\, x^2/(\ln R)^2 \qquad . \quad . \quad (7)$$

The lag t_1 of the temperature wave between any two depths is also derived from the temperature curves. Writing the second form of equation (5) again :

$$\alpha = \frac{1}{2\omega}\left(\frac{x}{t_1}\right)^2$$

or
$$\alpha = 697{\cdot}1\left(\frac{x}{t_1}\right)^2 \qquad . \quad . \quad . \quad (8)$$

when the numerical value of $\frac{1}{2\omega} = \frac{8760}{4\pi} = 697{\cdot}1$ has been inserted. The period is, of course, one year, as before. Equation (8) is in a form used for calculation.

The values of thermal capacity and density for the three soil layers were found from laboratory measurements on soil samples, and their product gave the volumetric heat capacity. On multiplying the diffusivity by the corresponding volumetric heat values the thermal conductivity for that soil layer was obtained.

EXPERIMENTAL PROCEDURE

Arrangements for Soil Temperature Measurement

Considerable experience in the technique of measuring soil temperatures had been gained in a previous smaller investigation in 1948. This experience indicated that it was preferable to use ordinary mercury in glass thermometers inside buried tubes rather than vapour pressure thermometers or thermocouples. Buried thermocouples would have ensured that the surface temperatures could not directly affect the indicated temperature and would almost certainly have been secure from malicious damage. However, accurate readings are difficult to obtain in field conditions, require more skill on the part of the observer, and involve the transport of fragile apparatus over rough tracks. Accordingly, this method was not adopted for general use but held in reserve for occasional application.

The apparatus used is illustrated in Fig 4. A brass oil bottle containing the thermometer rested at the bottom of an asbestos tube. At the lower end of the asbestos tube was a steel collar of the same height as the oil bottle. This steel collar ensured that the thermometer container was at mean effective ground temperature over the section of soil surrounding the collar. Both the collar and bottle were 6 inches in length, and accordingly, the mean effective depth was taken as 3 inches higher than the bottom of the hole. The container was a brass bottle filled with a light lubricating oil, and had a thermometer permanently in position. Baffles were included in the tube to minimize convection currents, and the metallic lifting

wires were made discontinuous to minimize direct heat flow down the tube. The top of the hole was closed by a tightly fitting wooden plug. Calibrated thermometers, capable of being read to within 0·1° F, were used. The observer read the thermometer immediately the oil bottle was raised to the surface, without stirring the oil, whilst standing between the sun and the thermometer. This method was found to give the most satisfactory results, and the reading so obtained was taken as the true one. In some confirmatory tests the observer, after taking the first reading, stirred the oil for about ½ min and then took another reading. It

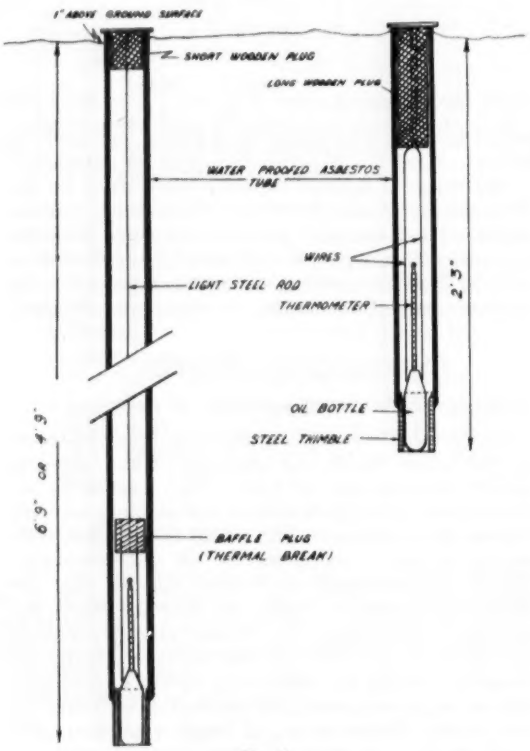


FIG 4

EARTH TEMPERATURE MEASUREMENT APPARATUS

is noteworthy that in certain conditions the thermometer declined on stirring due to evaporation of a film of moisture on the surface of the oil bottle. This effect was confined to the deeper holes. There was no question of the oil losing heat to the atmosphere as at this time air temperatures were higher than the oil. Subsequently a slow rise in temperature was obtained after the moisture film had disappeared. After this discovery the oil bottles were wiped with a dry cloth if any moisture was present.

At each of the fifty sites three depths were employed, as previously stated, namely 2 ft, 4½ ft, and 6½ ft nominal. Twenty-four of the sites were in Iraq and twenty-six in Syria. In general they were about 15 miles apart. In two sections where the soil varies considerably, namely between K-3 and T-1, and between T-2 and T-3, the spacing was reduced to approximately 5 miles. Where installations could not be placed in pump stations they were made as inconspicuous as possible by camouflage. Care was taken to avoid water channels and other sites liable to flooding in winter. During installation the soil was disturbed as little as possible. Earth augers were used with crowbars to loosen hard soil and soft rock. In some instances it was necessary to use a compressor driven rock drill for the deep holes in solid rock.

All sites were ready before the summer peak period of 1951, and observations were continued until after the summer peak of 1952. In this manner a series of 1½ cycles was obtained.

Temperature readings at all sites were taken regularly by observers making scheduled runs along the pipeline. This accounts for the varying and irregular intervals between observations, since at either end of his run the observer would take observations with only two days between them followed by an interval of perhaps two weeks. In the middle of his run the observations would be taken approximately once a week. This irregular feature was unfortunate, but could not be avoided. At the times of maximum and minimum an increased number of observations was obtained by employing a second observer. Delays were sometimes caused through tracks or rivers being impassable in winter and by mechanical breakdown of vehicles, but the overall effect was not serious. At particular sites readings might have to be omitted when Bedouin were grazing their flocks near by. Only in Homs Depot was it possible to arrange for earth temperatures to be read every working day.

The temperature curves (appended) often show pronounced irregularities. This is particularly the case in winter at 2 ft depth, and it had to be considered that these might be due to daily changes in weather at the surface affecting the thermometers directly by convection in the tube. This would seriously reduce the accuracy of all observations, and accordingly in the early part of 1952 a check was made in Homs Depot. It may be remarked that the climate of Homs is cold, stormy, and wet in winter. In this check, oil bottles similar to those normally in use were buried at the same depths as those in the tubes only a few yards away, and the augered holes completely backfilled. Each such bottle had two calibrated copper–constantan thermocouples immersed in the oil, with the leads running to the surface inside rubber tubing. This arrangement gave the necessary insulation and strength. The thermocouple e.m.f. were read daily using a Cambridge potentiometer with melting ice for the reference standard. The temperatures so obtained were plotted against the corresponding ground temperatures as given by the thermometers. The test was continued for three months. The two sets of results corresponded closely over a period when there were many

irregularities. This was accepted as proof that the thermometers in the tubes did in fact read soil temperature and were not affected directly by surface conditions to any serious extent.

Strong confirmation of the intrinsic verity of the thermometer readings is afforded by a detailed study of individual temperature curves. Irregularities in the 2-ft curve tend to be repeated with diminishing amplitude and increasing lag in the 4½-ft and 6½-ft curves. Examples of this effect may be seen at

Mile 32	August 1951 February and April 1952
Mile 234	August 1951 April 1952
Mile 353	August 1951 March 1952
Homs	December 1951 April 1952
Banias	April and November 1951

Numerous other cases may also be detected.

Laboratory Determinations of Soil Density and Specific Heat

Samples of various soils at appropriate depths were obtained from all locations and their specific heat and density measured. The product of specific heat and density is the volumetric heat capacity. It is this quantity which is required for transformation of diffusivity to conductivity

$$\text{Diffusivity} = \frac{\text{Conductivity}}{\text{Specific heat} \times \text{Density}}$$

Contrary to published statements, wide differences were found between the volumetric heat capacity of the various soil samples. Values varying between 17 and 38 B.T.U/cu. ft/° F were noted. The moisture content was determined only for soils from the Homs to Banias section, where winter rainfall is fairly high. It was assumed that the moisture content of desert ground at the depths concerned would be small and substantially constant throughout the year. In any case, such data would be difficult to apply to diffusivity calculated from the temperature wave for a whole year. Accordingly, the moisture content was not determined for such locations.

Density was determined by volumetric displacement of fine sand followed by direct weighing of the sample in air. In sampling, the specimens had been obtained so far as possible in large lumps. This procedure gave the bulk density of the specimen as it had been when in its original position. Subsequently the fragments of soil were recovered from the sand by sieving. In some few cases soil densities were taken *in situ*.

The specific heats of the soil specimens were measured by the method of mixtures. Aluminium alloy pellets were used as the reference standard. Water was not used as a standard, since some types of soil possess a heat of absorption. No other available fluid had suitable properties, and all had the disadvantage that the sample tested could not be used again. Aluminium was chosen for the reference standard because its high specific heat and low density gave it a volumetric heat capacity similar to that of most soils. By this means it was possible to work with mixtures in which the two components were of approximately equal volume and heat capacity, and thus the temperature changes of the two components were also approximately equal. These factors tend to minimize errors due to thermometer readings. Magnesium would have been even more suitable as a reference standard from the point of view of volumetric heat capacity, but was ruled out on account of its reaction with water even at ordinary temperatures.

From the beginning it was recognized that the accurate measurement of the temperature of a small mass of soil particles would not be an easy matter. Similarly the interchange of heat between the aluminium pellets and the soil could not but be a slow process. To promote thorough stirring and interchange of heat inclined rotating calorimeters (Fig 5) were devised. Cylinders A and B are polished lightweight copper calorimeters. The rotation of these calorimeters at a suitable angle provided a thorough

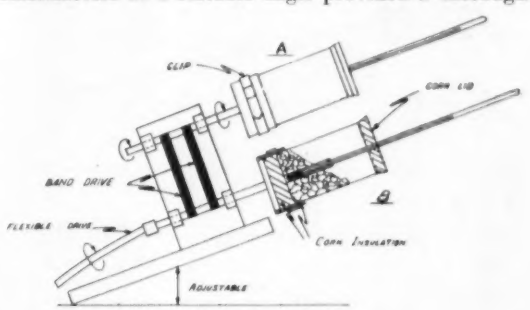


FIG 5

INCLINED ROTATING CALORIMETERS FOR MEASURING SPECIFIC HEAT OF SOIL BY ADMIXTURE WITH ALUMINIUM PELLETS

agitation of their contents. This method of stirring was adopted by analogy with a ball-mill as providing a convenient method of mixing solid particles. The most effective angle of inclination was found by inspection of the rotating contents. A central tube of copper foil soldered to the bottom of the calorimeter provided support and protection to the thermometer. It was hoped also that this feature would provide a conducting path from all depths of the rotating mass to the bulb of the thermometer and thereby give a more truly representative temperature. Accurate open-scale thermometers reading to within 0·1° F were employed.

The water equivalent of the calorimeter B was measured in the usual way. A weighed quantity of warm water was placed in calorimeter A and of chilled water in calorimeter B. Both cylinders were then rotated steadily and continuously for several minutes. At 30-sec intervals the rotation was halted to read the temperature of one or the other alternately. When steady cooling and heating curves had been established the warm water was quickly poured into calorimeter B, the time of mixing being

noted to the nearest second. After mixing the calorimeter was rotated for a further 15 minutes. Temperatures were read at 30-sec intervals as before. By graphing the several heating and cooling curves the respective temperatures at the instant of mixing were determined by extrapolation, and the water equivalent of the calorimeter B with its allocated thermometer calculated. The mean value of fifteen such determinations was found to be 15·3 g with a probable error of 1·3 per cent amongst themselves.

Proceeding along similar lines the specific heat of the aluminium alloy pellets was then determined, and as a result of five tests was found to be 0·189 with a probable error of 0·2 per cent amongst themselves. The accuracy of these determinations is decidedly higher than the later ones on the soil samples owing to the greater facility of heat exchange.

Subsequently the specific heat of the soil samples was measured by a similar procedure. In this case

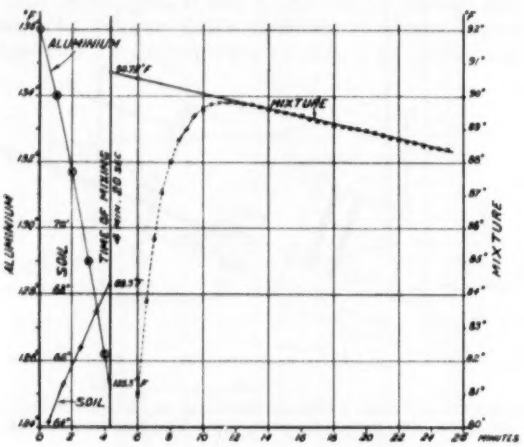


FIG 6

SPECIFIC HEAT DETERMINATION

Typical temperature curves before and after mixing

the warm aluminium pellets were decanted into the chilled soil. It was necessary to continue the observation of temperatures over a longer period amounting to about 20 minutes, since the temperature equalization process was slower. The experiments were so arranged that the water equivalent of the calorimeter was approximately one-fifth of the whole. The most important source of error was the estimation of temperature at the instant of mixing. This error was minimized by so arranging the respective quantities that the temperature rise of the chilled soil was approximately the same as the fall in temperature of the hot aluminium pellets. Moreover, the temperature of the mixture was planned to be only slightly above that of the laboratory. This gave a final cooling curve of gentle slope, and in this manner maximum precision was obtained from the lengthy extrapolation required. A typical set of curves is shown in Fig 6.

CALCULATION OF THERMAL CONDUCTIVITIES

Temperature waves are available from the fifty sites for the three depths of 2 ft, 4½ ft, and 6½ ft, as appended in reduced form. The several soil layers for which the conductivity was determined have been classified as follows:

Layer A 2–6½ ft, *i.e.* mean depth = 4 ft 3 in
Layer B 2–4½ ft, ,, ,, ,, = 3 ft 3 in
Layer C 4½–6½ ft, ,, ,, ,, = 5 ft 6 in

The foregoing depths are nominal; in the calculation measured depths were used.

The expressions from which the diffusivity of the soil layers were calculated from the temperature waves are:

From Amplitude Ratio: Equation (7).
From lag: Equation (8).

Furthermore,

Thermal conductivity = Diffusivity × Specific heat × Density

The specific heat and density for the several soil layers at each site were determined in the laboratory as described in the previous section. The thermal conductivity could thus be calculated.

In theory both the amplitude ratio and lag expressions for calculating diffusivity are equally valid. In practice, however, it appears that the amplitude ratio may be determined with decidedly greater accuracy than the lag. In treatment of the results both methods were used for all sites. Subsequently the two series of figures were weighted statistically. The relative weights were then used to combine the two values for every layer and site.

TABLE I

Probable Error (Per Cent) in Pipeline Section Average Conductivities

	n	$\frac{1}{\sqrt{n}}$	Layer		
			A	B	C
K-1–K-2 . .	3	0·58	4·0	5·5	5·4
K-2–K-3 . .	6	0·41	2·8	3·9	3·8
K-3–T-1 . .	11	0·30	2·1	2·8	2·8
T-1–T-2 . .	5	0·45	3·1	4·3	4·2
T-2–T-3 . .	12	0·29	2·0	2·8	2·7
T-3–T-4 . .	4	0·50	3·4	4·8	4·6
T-4–M-466 . .	3	0·58	4·0	5·5	5·4
M-466–Banias .	7	0·38	2·6	3·6	3·5
Average for pipeline	51	0·14	1·0	1·3	1·3
Single observation .	1	1·00	6·9	9·5	9·3

n = number of values available from each section.

In making use of the curves it was necessary to take into account the marked irregularity of some of them. Those from 2 ft in particular show obvious departures from the sinusoidal form. Since it had been proved

TABLE II

Full Record of Soil Thermal Conductivities, Specific Heats, and Densities

Location by miles from K-1	Notes on nature of ground	Soil layer	Density	Spec. heat	k_R	k_L	k Layer B (2–4½ ft)	k Layer A (2–6½ ft)	k Layer C (4½–6½ ft)
0 (K-1)	Deep alluvial soil with very few pebbles	B	111	0·229	0·56	0·60	0·57	—	—
		A	108	0·215	0·58	0·54	—	0·57	—
		C	106	0·201	0·63	0·49	—	—	0·61
32		B	117	0·189	0·28	0·42	0·32	—	—
		A	118	0·208	0·39	0·47	—	0·41	—
		C	120	0·226	0·58	0·53	—	—	0·58
54 (Fatha) (Gorge)	Tigris River alluvial gravels	B	91	0·211	0·24	0·30	0·25	—	—
		A	91	0·211	0·26	0·31	—	0·27	—
		C	91	0·211	0·29	0·34	—	—	0·30
66 (K-2)	Deep sand with some consolidation	B	100	0·166	0·21	0·41	0·26	—	—
		A	100	0·166	0·24	0·39	—	0·27	—
		C	100	0·166	0·30	0·36	—	—	0·31
80		B	100	0·192	0·25	0·45	0·30	—	—
		A	100	0·192	0·25	0·44	—	0·29	—
		C	100	0·192	0·26	0·44	—	—	0·28
99	Marls overlying massive gypsum or rotten limestone. Subsoil frequently rocky. Numerous outcrops	B	107	0·221	0·41	0·27	0·37	—	—
		A	110	0·225	0·42	0·32	—	0·40	—
		C	112	0·228	0·43	0·39	—	—	0·43
110		B	120	0·261	0·29	0·40	0·32	—	—
		A	122	0·263	0·39	0·44	—	0·40	—
		C	125	0·266	0·65	0·50	—	—	0·64
122		B	75	0·220	0·14	0·16	0·15	—	—
		A	89	0·231	0·19	0·29	—	0·21	—
		C	108	0·242	0·29	0·62	—	—	0·32
136		B	90	0·227	0·13	0·16	0·14	—	—
		A	93	0·233	0·20	0·23	—	0·21	—
		C	97	0·239	0·38	0·39	—	—	0·38
150 (K-3)		B	87	0·244	0·14	0·44	0·23	—	—
		A	96	0·236	0·21	0·51	—	0·27	—
		C	106	0·227	0·38	0·61	—	—	0·40
155		B	74	0·267	0·16	0·30	0·20	—	—
		A	74	0·267	0·20	0·34	—	0·23	—
		C	74	0·267	0·27	0·40	—	—	0·29
161	Marls overlying marly limestone. Numerous outcrops	B	112	0·177	0·20	0·32	0·23	—	—
		A	116	0·173	0·31	0·31	—	0·31	—
		C	119	0·169	0·64	0·29	—	—	0·60
166		B	94	0·192	0·21	0·33	0·24	—	—
		A	94	0·192	0·22	0·33	—	0·24	—
		C	94	0·192	0·22	0·33	—	—	0·23
172		B	92	0·185	0·16	0·25	0·18	—	—
		A	92	0·185	0·20	0·25	—	0·21	—
		C	92	0·185	0·29	0·25	—	—	0·28
177		B	107	0·181	0·22	0·29	0·24	—	—
		A	107	0·181	0·29	0·41	—	0·32	—
		C	107	0·181	0·43	0·67	—	—	0·46
184		B	93	0·202	0·24	0·24	0·24	—	—
		A	93	0·202	0·19	0·26	—	0·21	—
		C	93	0·202	0·16	0·28	—	—	0·17
190		B	117	0·198	0·20	0·30	0·23	—	—
		A	116	0·198	0·27	0·31	—	0·28	—
		C	115	0·198	0·43	0·34	—	—	0·42
194		B	92	0·289	0·20	0·33	0·24	—	—
		A	87	0·280	0·24	0·30	—	0·25	—
		C	82	0·272	0·33	0·28	—	—	0·32

TABLE II—*continued*

Location by miles from K-1	Notes on nature of ground	Soil layer	Density	Spec. heat	k_R	k_L	k Layer B (2–4½ ft)	k Layer A (2–6½ ft)	k Layer C (4½–6½ ft)
199	Marls overlying marly limestone. Numerous outcrops —*continued*	B	102	0·204	0·27	0·40	0·30	—	—
		A	102	0·214	0·23	0·33	—	0·25	—
		C	101	0·223	0·19	0·27	—	—	0·20
205		B	90	0·230	0·16	0·18	0·17	—	—
		A	93	0·222	0·18	0·22	—	0·19	—
		C	96	0·215	0·21	0·31	—	—	0·22
210 (T-1)		B	93	0·207	0·19	0·33	0·23	—	—
		A	98	0·196	0·18	0·27	—	0·20	—
		C	104	0·184	0·16	0·21	—	—	0·16
223		B	98	0·207	0·21	0·20	0·20	—	—
		A	100	0·207	0·29	0·25	—	0·28	—
		C	101	0·208	0·49	0·35	—	—	0·48
234	Light sandy clay thinly overlying sandy limestone	B	105	0·193	0·28	0·32	0·29	—	—
		A	105	0·193	0·40	0·36	—	0·39	—
		C	105	0·193	0·71	0·44	—	—	0·68
247		B	112	0·182	0·43	0·60	0·48	—	—
		A	112	0·180	0·42	0·55	—	0·45	—
		C	111	0·175	0·40	0·48	—	—	0·41
264		B	129	0·201	0·57	0·59	0·57	—	—
		A	122	0·183	0·45	0·67	—	0·50	—
		C	115	0·165	0·35	0·84	—	—	0·40
279 (T-2)		B	125	0·185	0·21	0·41	0·27	—	—
		A	120	0·204	0·27	0·45	—	0·31	—
		C	115	0·224	0·39	0·49	—	—	0·40
287		B	97	0·228	0·16	0·38	0·22	—	—
		A	97	0·228	0·20	0·32	—	0·22	—
		C	97	0·228	0·26	0·27	—	—	0·26
294		B	100	0·194	0·31	0·32	0·31	—	—
		A	100	0·191	0·42	0·41	—	0·42	—
		C	99	0·188	0·67	0·59	—	—	0·66
301		B	87	0·199	0·42	0·47	0·43	—	—
		A	85	0·194	0·44	0·44	—	0·44	—
		C	82	0·189	0·48	0·41	—	—	0·47
307		B	112	0·206	0·44	0·49	0·45	—	—
		A	112	0·206	0·50	0·40	—	0·48	—
		C	112	0·206	0·60	0·32	—	—	0·57
313		B	110	0·180	0·40	0·35	0·38	—	—
		A	110	0·180	0·52	0·42	—	0·50	—
		C	110	0·180	0·77	0·54	—	—	0·74
320	Little soil cover in this section	B	151	0·165	0·52	0·58	0·54	—	—
		A	166	0·156	0·53	0·62	—	0·55	—
		C	185	0·144	0·52	0·66	—	—	0·53
326		B	150	0·162	0·50	0·48	0·49	—	—
		A	153	0·163	0·70	0·59	—	0·67	—
		C	155	0·164	1·29	0·78	—	—	1·24
330		B	130	0·167	0·30	0·41	0·33	—	—
		A	134	0·169	0·40	0·47	—	0·42	—
		C	142	0·173	0·64	0·58	—	—	0·63
338	Palmyra Basin. Mainly alluvial with occasional outcrops of limestone or sandstone	B	107	0·214	0·22	0·26	0·23	—	—
		A	104	0·233	0·30	0·31	—	0·30	—
		C	100	0·254	0·48	0·40	—	—	0·47
346		B	106	0·147	0·41	0·43	0·41	—	—
		A	106	0·162	0·36	0·37	—	0·36	—
		C	105	0·180	0·31	0·32	—	—	0·31
353		B	110	0·182	0·46	0·61	0·50	—	—
		A	117	0·157	0·38	0·38	—	0·38	—
		C	125	0·142	0·33	0·25	—	—	0·32

TABLE II—*continued*

Location by miles from K-1	Notes on nature of ground	Soil layer	Density	Spec. heat	k_R	k_L	k Layer B (2–4½ ft)	k Layer A (2–6½ ft)	k Layer C (4½–6½ ft)
360 (T-3)	Palmyra Basin. Mainly alluvial with occasional outcrops of limestone or sandstone —*continued*	B	103	0·164	0·18	0·18	0·18	—	—
		A	103	0·164	0·30	0·29	—	0·30	—
		C	103	0·164	0·72	0·68	—	—	0·71
376		B	107	0·166	0·22	0·34	0·25	—	—
		A	114	0·163	0·24	0·32	—	0·25	—
		C	121	0·159	0·25	0·29	—	—	0·25
396		B	94	0·190	0·34	0·29	0·32	—	—
		A	96	0·193	0·31	0·30	—	0·31	—
		C	99	0·196	0·28	0·33	—	—	0·29
403		B	116	0·151	0·40	0·46	0·41	—	—
		A	115	0·154	0·42	0·52	—	0·44	—
		C	113	0·156	0·45	0·59	—	—	0·47
421 (T-4)	Rolling hills. Light sandy clay overlying limestone	B	86	0·258	0·29	0·29	0·29	—	—
		A	86	0·250	0·30	0·33	—	0·31	—
		C	87	0·241	0·32	0·40	—	—	0·33
435		B	89	0·165	0·27	0·23	0·26	—	—
		A	86	0·168	0·23	0·26	—	0·23	—
		C	83	0·172	0·19	0·31	—	—	0·21
455	Terra Rossa. Reddish fertile clay with limestone at depth Soil moisture 15 per cent May 1952 at 3-ft depth at Homs	B	106	0·229	0·21	0·31	0·24	—	—
		A	110	0·212	0·24	0·31	—	0·25	—
		C	115	0·194	0·28	0·32	—	—	0·29
479 (Homs)		B	117	0·232	0·34	0·42	0·37	—	—
		A	117	0·232	0·48	0·53	—	0·49	—
		C	117	0·232	0·81	0·76	—	—	0·81
506	Heavy dark fertile clay with numerous basalt boulders Soil moisture 10 per cent July 1952 at 3½ft depth	B	122	0·307	0·68	0·38	0·59	—	—
		A	122	0·307	0·72	0·46	—	0·67	—
		C	122	0·307	0·78	0·61	—	—	0·76
515	Coastal hills. Reddish fertile clay overlying limestone. Moisture content M.515, July 1952: 2 ft 8%, 3½ ft 15%, 5½ ft 2%	B	122	0·230	0·71	0·88	0·76	—	—
		A	138	0·187	0·78	0·84	—	0·79	—
		C	154	0·144	0·84	0·75	—	—	0·83
529		B	108	0·220	0·53	0·37	0·49	—	—
		A	108	0·220	0·60	0·54	—	0·59	—
		C	108	0·220	0·71	0·95	—	—	0·73
530		B	108	0·241	0·35	0·46	0·38	—	—
		A	108	0·241	0·50	0·59	—	0·52	—
		C	108	0·241	0·88	0·83	—	—	0·88
542	Coastal plain. Heavy dark fertile clay with numerous basalt boulders. Moisture content, July 1952, M.542 and 556, 3½ ft 14% both locations	B	116	0·330	0·73	0·55	0·68	—	—
		A	116	0·330	0·68	0·51	—	0·64	—
		C	116	0·330	0·63	0·46	—	—	0·61
556 (Banias)		B	132	0·236	0·70	0·59	0·67	—	—
		A	128	0·246	0·66	0·64	—	0·66	—
		C	124	0·257	0·62	0·73	—	—	0·63

k_R = Thermal conductivity from amplitude ratio (B.T.U/sq. ft/hr/1° F/ft)
k_L = Thermal conductivity from lag (B.T.U/sq. ft/hr/1° F/ft)
k = Weighted mean value according to estimated accuracies of k_R and k_L
Soil layer B is layer between 2 ft and 4½ ft giving 3 ft 3 in mean depth
Soil layer A is layer between 2 ft and 6½ ft giving 4 ft 3 in mean depth
Soil layer C is layer between 4½ ft and 6½ ft giving 5 ft 6 in mean depth
Soil density in lb/cu. ft.
Soil specific heat numerically equal to thermal capacity in B.T.U/lb/1° F

that the recorded figures were true soil temperatures they could not be ignored as errors of observation. The irregularities having been proved to be real it seemed clear that they could be represented by higher harmonics superimposed on the fundamental heat wave. The problem then was how best to determine the amplitude and lag. It seemed incorrect to take the extreme maxima and minima as representative, since these were obviously excrescences on the main curve in many cases. This is particularly true of the

2-ft winter figures. Two methods of treatment seemed possible, from either of which the amplitude and lag could be obtained.

(*a*) to extract the fundamental curves by Fourier Analysis;
(*b*) to draw in supposititious curves by eye.

The extraction of the fundamental is a straightforward but laborious process. It provides an objective method of dealing with the irregular temperature curves for any given year. The alternative—drawing a smooth supposititious curve by eye through irregularities—is very much quicker, but the results depend to some extent on judgment. Accordingly, it was decided to analyse the temperature curves for five representative locations and compare the diffusivity values thus obtained with those derived from supposititious curves. No significant difference between the results obtained from harmonic analysis and the supposititious curves was found, and therefore the latter were used in every case.

The curves in most cases include two summer maxima and one winter minimum. Thus for each layer two values of amplitude are available. For the lag two values were obtained from the summer peaks and two more from the mean temperature. This latter point on the curve is preferable to the winter minimum, which is usually ill-defined in time. The lag, of course, could be taken between any two corresponding phases on the respective curves.

The two methods of amplitude ratio and lag were used to evaluate the conductivity for each layer and site. These are the figures listed as k_R and k_L in Table II. In order to obtain the best final values the two methods were examined from the standpoint of experimental errors. The probable errors involved in the several measurements were estimated by the usual statistical methods, and are tabulated below.

Probable Errors in Measurements

Soil temperature:			
Individual observations, ° F	0·2		
Values read off from plotted curves, ° F	0·3		
Depth of installations, ft	0·007		
Specific heat of soil, %	3·4		
Density of soil, %	2·5		
Layer:	A	B	C
Temperature wave lag, %	7·2	8·9	13
Depth, ft:	2	4½	6½
Annual temperature range, %	2·0	0·7	1·1

From the foregoing it was calculated that the probable errors (per cent) of the several individual conductivities are:

Layer:	A	B	C
Conductivity by amplitude ratio method	8	11	10
Conductivity by lag method	15	18	28

Taking into consideration these probable errors in the two series of figures k_R and k_L, relative weights were calculated to be the figures below:

Relative Weights

Layer:	A	B	C
Amplitude ratio method	0·79	0·72	0·89
Lag method	0·21	0·28	0·11

The foregoing relative weights were used to combine the pairs of values for conductivity k_R and k_L in such a way as to obtain the best figure. This latter is the final weighted mean conductivity k listed by sites in Table II.

The process of combination has the effect of reducing the probable error of the final figure. Taking all factors and sources of error into consideration, the probable errors of weighted conductivities for individual sites are:

Layer:	A	B	C
Probable error, %	7	10	9

For the purpose of predicting oil temperatures the weighted conductivities from individual sites are best combined into representative values to be employed for the whole of particular pipeline sections between pump stations. This process has the effect of further reducing the probable error for the several sections as may be seen in Table I.

TABLE III

Concise Table of Soil Thermal Conductivities

Section	Weighted Mean Values		
	Layer B (2–4½ ft) (Mean = 3½ ft)	Layer A (2–6½ ft) (Mean = 4½ ft)	Layer C (4½–6½ ft) (Mean = 5½ ft)
	B.T.U/sq. ft/hr/° F/ft		
K-1–K-2	0·38	0·42	0·50
K-2–K-3	0·26	0·30	0·39
K-3–T-1	0·23	0·23	0·33
T-1–T-2	0·36	0·36	0·43
T-2–T-3	0·38	0·42	0·55
T–T-4	0·29	0·32	0·43
T-4–M-466	0·26	0·26	0·27
M-466–Banias	0·56	0·62	0·75

Application of Results to Oil Temperature Predictions

The usual formula derived for calculating the temperature of the oil at any point along a buried pipeline [1] may be written:

$$T_L = T_0 + \left(T_h + \frac{H}{A} - T_0\right)\left(1 - e^{-\frac{AL}{mc_0}}\right) \quad (9)$$

Equation (9) holds for steady conditions only. After any change in throughput some time will elapse before the new steady temperature is reached; and a more complicated treatment would be needed to calculate the transient conditions. The derivation of equation (1) assumes a soil of uniform conductivity, and in practice it is necessary to use the average effective value for sections of suitable length. No allowance is made for the resistance to heat flow from the surface to the air, where the heat is eventually dissipated, and this could be compensated for by an

TABLE IV

Concise Tables of Average Monthly Soil Temperatures (° F)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2-ft depth												
K-1–K-2	56	57	59	68	76	85	91	93	91	82	73	63
K-2–K-3	57	58	61	69	75	80	86	87	86	80	72	64
K-3–T-1	55	57	59	68	73	78	83	84	83	77	70	63
T-1–T-2	56	57	59	68	73	79	84	85	84	78	70	63
T-2–T-3	52	54	56	67	73	78	84	85	83	76	67	59
T-3–T-4	51	53	55	65	72	78	83	85	83	76	67	58
T-4–M-466	50	51	52	61	66	73	77	79	78	72	63	55
M-466–Banias	55	56	56	64	70	78	84	85	84	76	68	60
4½-ft depth												
K-1–K-2	65	63	63	66	72	78	84	87	88	84	79	72
K-2–K-3	66	64	64	67	71	75	79	82	83	81	76	72
K-3–T-1	64	63	62	66	69	73	77	79	80	78	73	69
T-1–T-2	63	62	61	65	69	74	78	81	81	79	74	69
T-2–T-3	60	59	59	64	68	74	78	80	80	78	72	66
T-3–T-4	59	58	58	64	67	73	76	79	80	77	72	66
T-4–M-466	57	56	55	59	63	67	71	74	74	72	68	63
M-466–Banias	60	59	59	63	67	72	77	80	81	78	72	65
6½-ft depth												
K-1–K-2	70	67	65	67	71	75	80	83	85	84	80	75
K-2–K-3	70	67	66	67	70	73	76	79	80	80	77	74
K-3–T-1	68	66	65	66	68	71	74	76	77	77	75	72
T-1–T-2	67	65	64	66	68	72	75	78	79	78	75	71
T-2–T-3	64	62	61	64	67	70	75	77	78	77	74	70
T-3–T-4	64	60	60	63	66	70	73	77	77	76	73	69
T-4–M-466	61	59	58	59	62	65	68	70	72	72	69	66
M-466–Banias	64	62	61	63	65	69	74	77	78	77	74	68

Note: The soil temperatures tabulated above were derived from field observation for the year ending 30 June 1952. Section average values were rounded off to the nearest degree. Soil temperatures at intermediate depths can be obtained without serious error by linear interpolation.

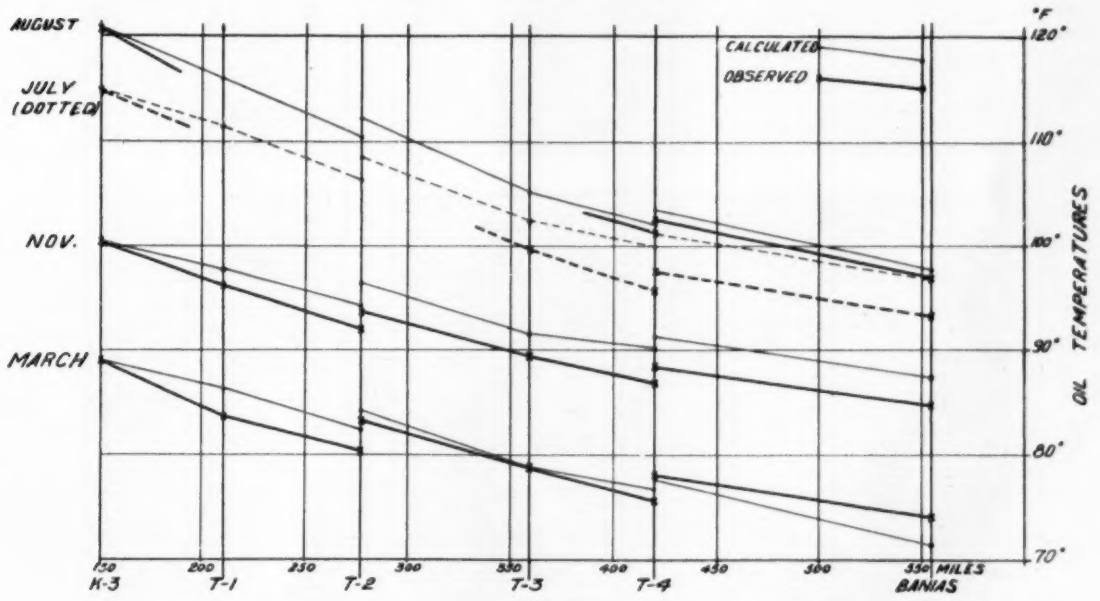
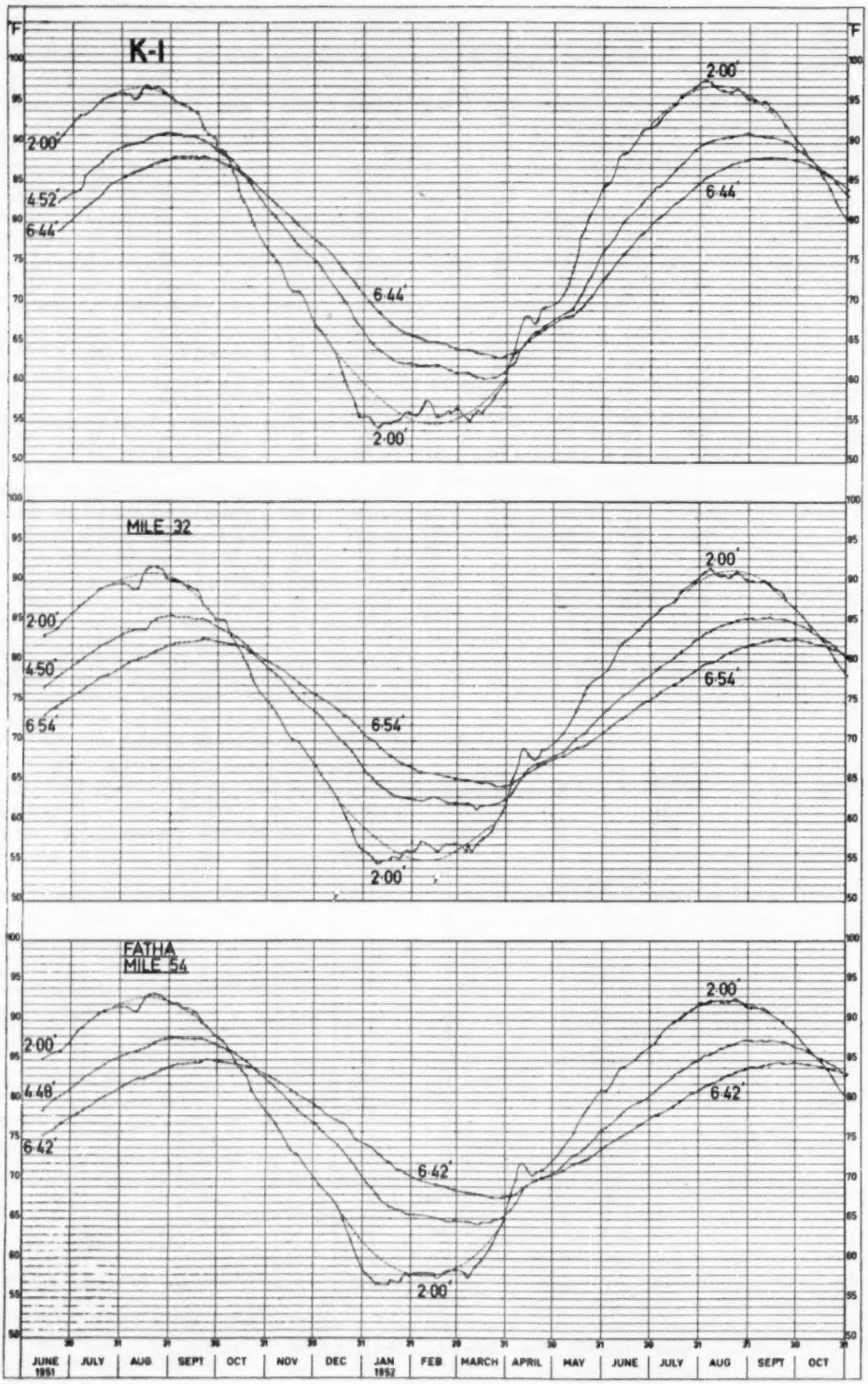


FIG 7

30-INCH LINE OIL TEMPERATURE—COMPARISON OF CALCULATED AND OBSERVED VALUES


K-1
2·00'
4·52'
6·44'
6·44'
2·00'
2·00'
6·44'
MILE 32
2·00'
4·50'
6·54'
6·54'
2·00'
2·00'
6·54'
FATHA
MILE 54
2·00'
4·48'
6·42'
6·42'
2·00'
2·00'
6·42'
JUNE 1951
JULY
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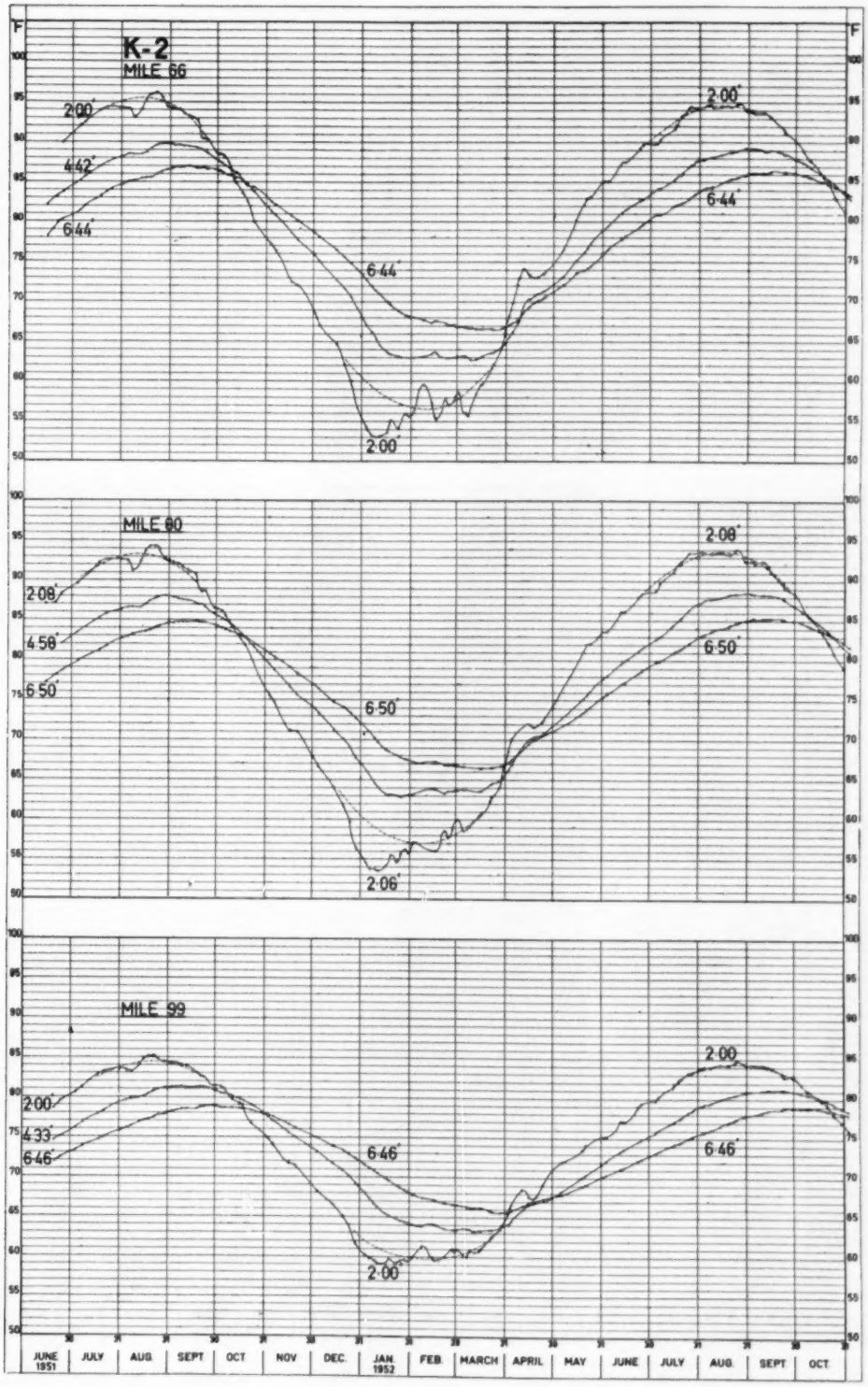
K-2
MILE 66
2·00
4·42
6·44
6·44
2·00
2·00
6·44
MILE 80
2·08
4·58
6·50
6·50
2·06
2·08
6·50
MILE 99
2·00
4·33
6·46
6·46
2·00
2·00
6·46
F
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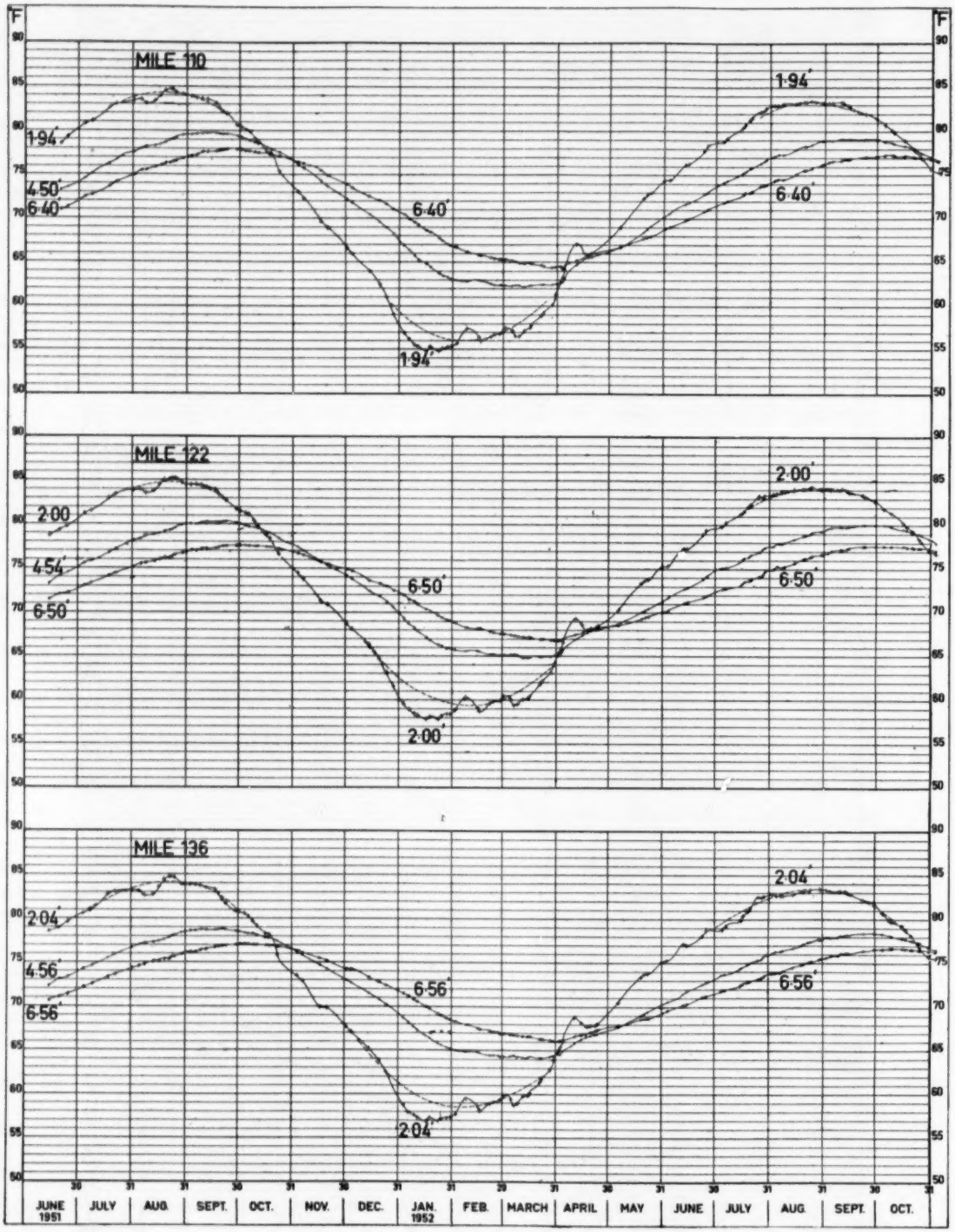
F
MILE 110
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4·50'
6·40'
6·40'
1·94'
1·94'
6·40'
MILE 122
2·00'
4·54'
6·50'
6·50'
2·00'
2·00'
6·50'
MILE 136
2·04'
4·56'
6·56'
6·56'
2·04'
2·04'
6·56'
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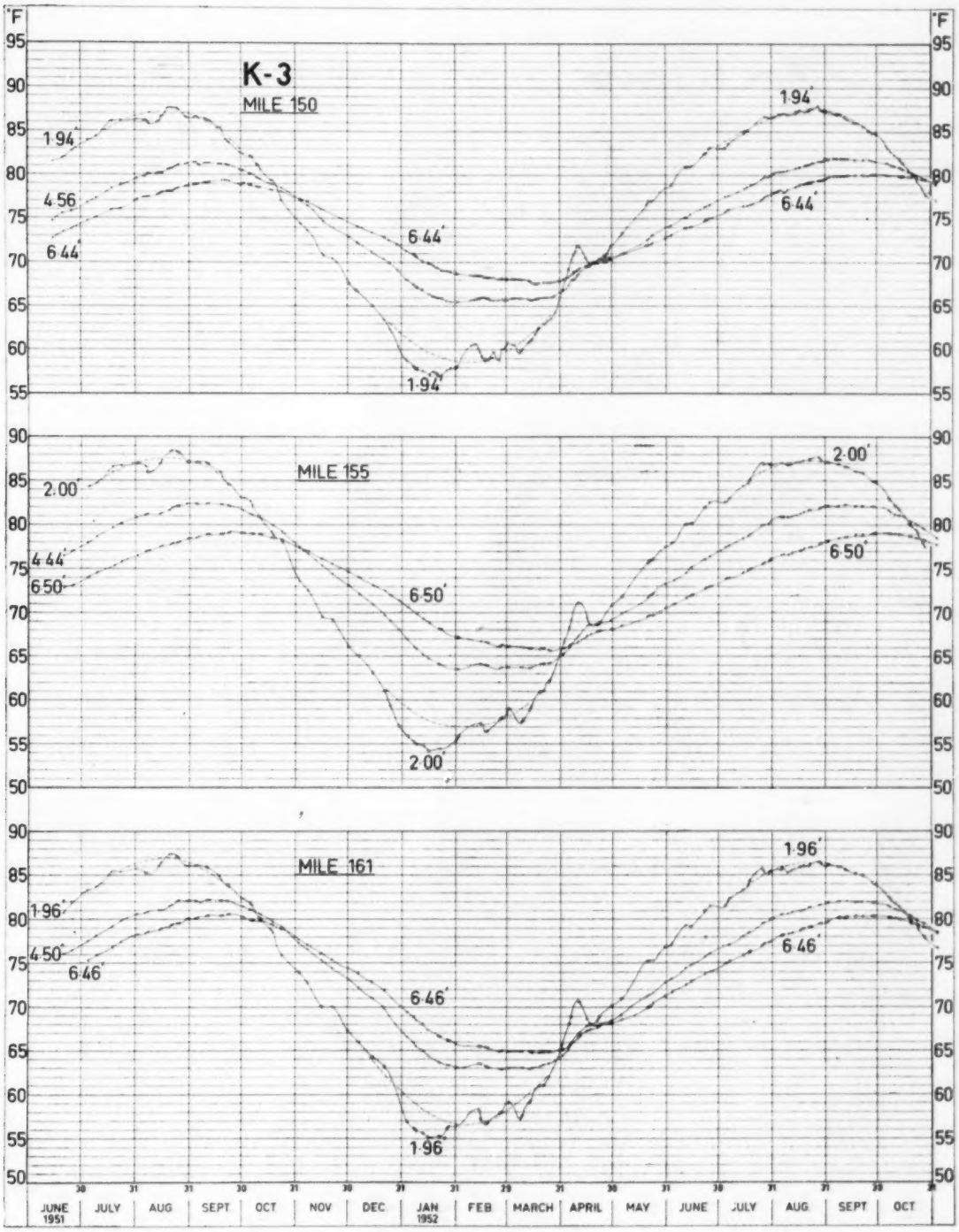
°F
K-3
MILE 150
1·94
4·56
6·44
6·44
1·94
1·94
6·44
MILE 155
2·00
4·44
6·50
6·50
2·00
2·00
6·50
MILE 161
1·96
4·50
6·46
6·46
1·96
1·96
6·46
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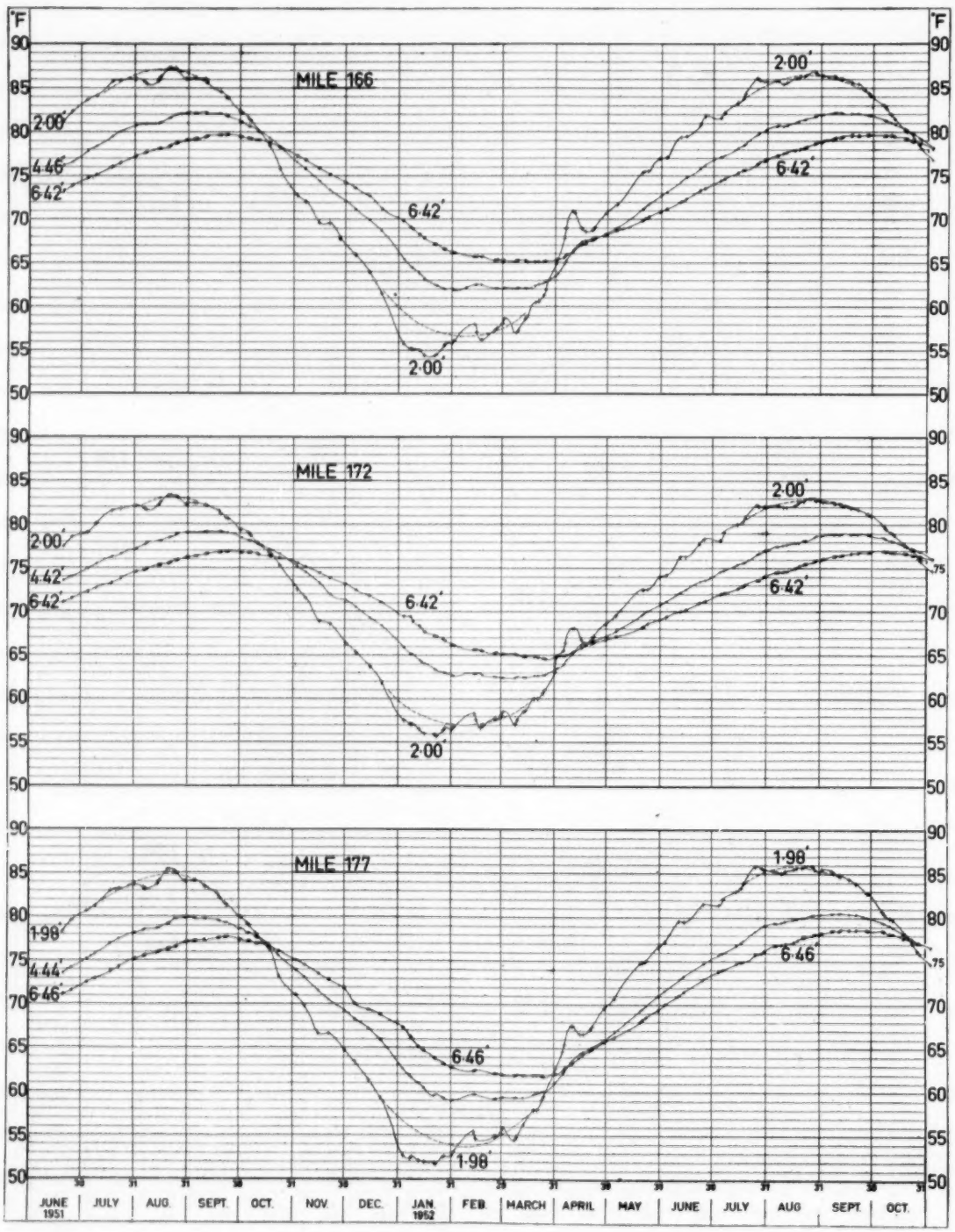
°F
MILE 166
2·00'
4·46'
6·42'
6·42'
2·00'
2·00'
6·42'
MILE 172
2·00'
4·42'
6·42'
6·42'
2·00'
2·00'
6·42'
MILE 177
1·98'
4·44'
6·46'
6·46'
1·98'
1·98'
6·46'
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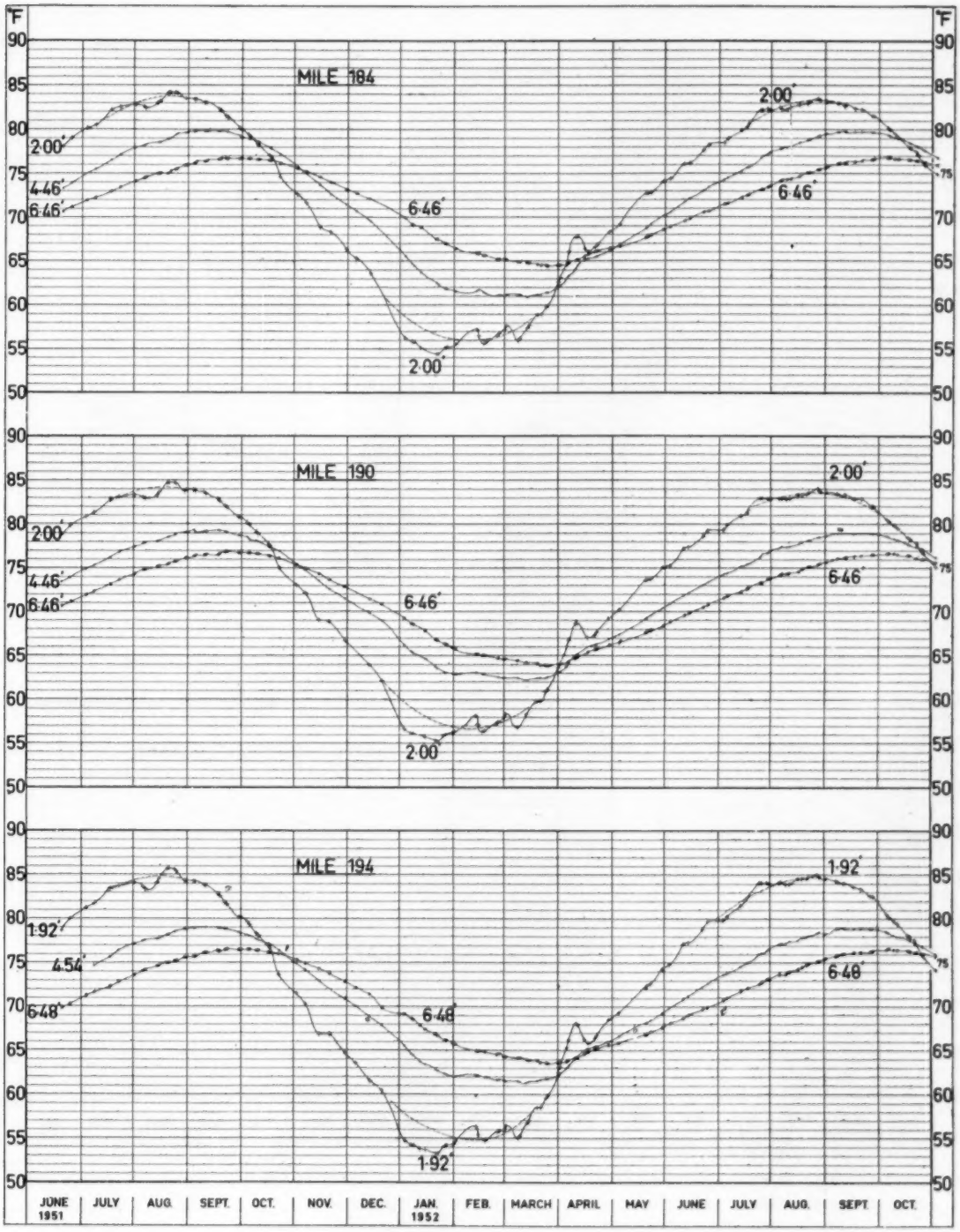
°F
MILE 184
2·00'
4·46'
6·46'
MILE 190
MILE 194
1·92'
4·54'
6·48'
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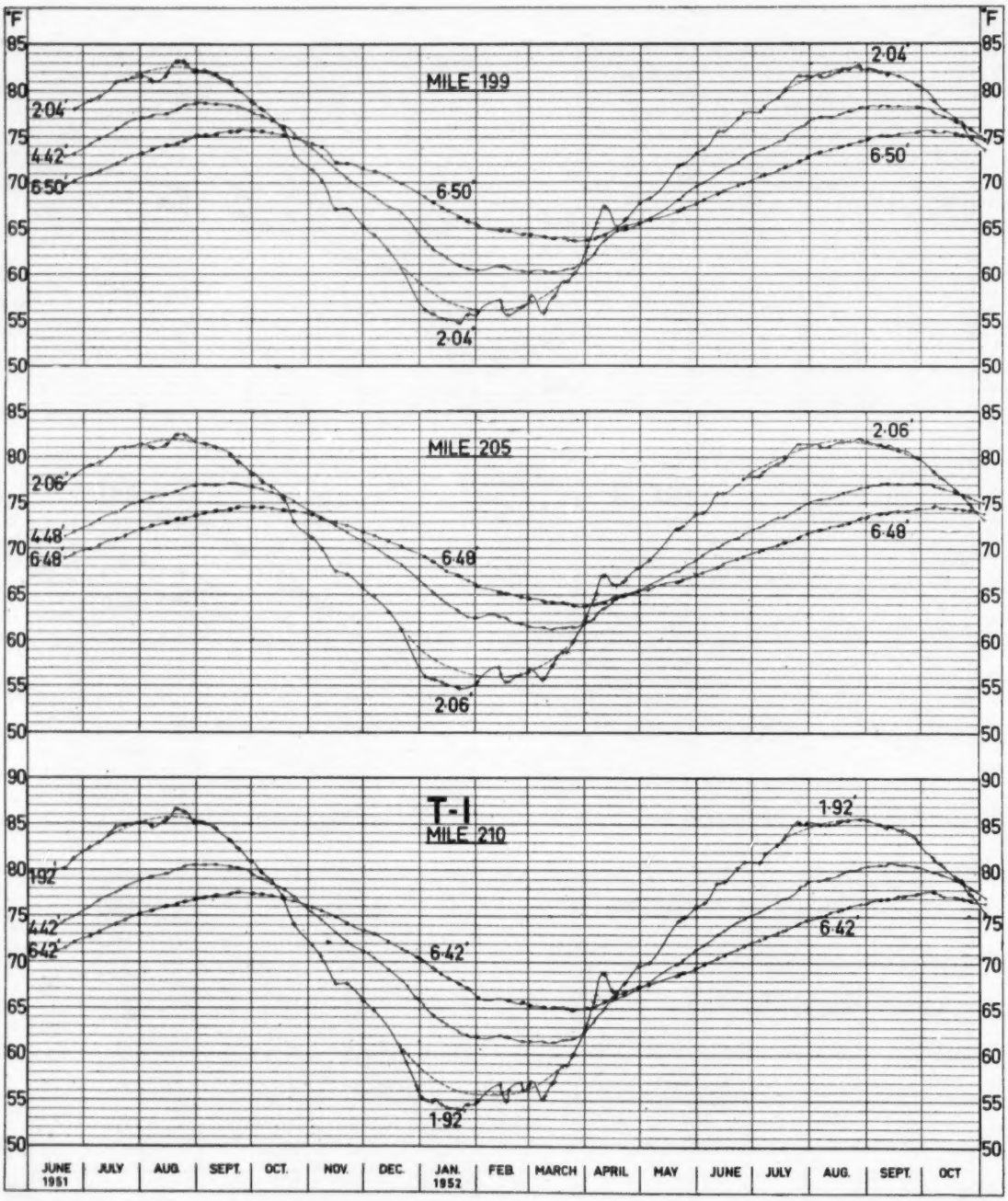
°F
MILE 199
2·04'
4·42'
6·50'
MILE 205
2·06'
4·48'
6·48'
T-1
MILE 210
1·92'
4·42'
6·42'
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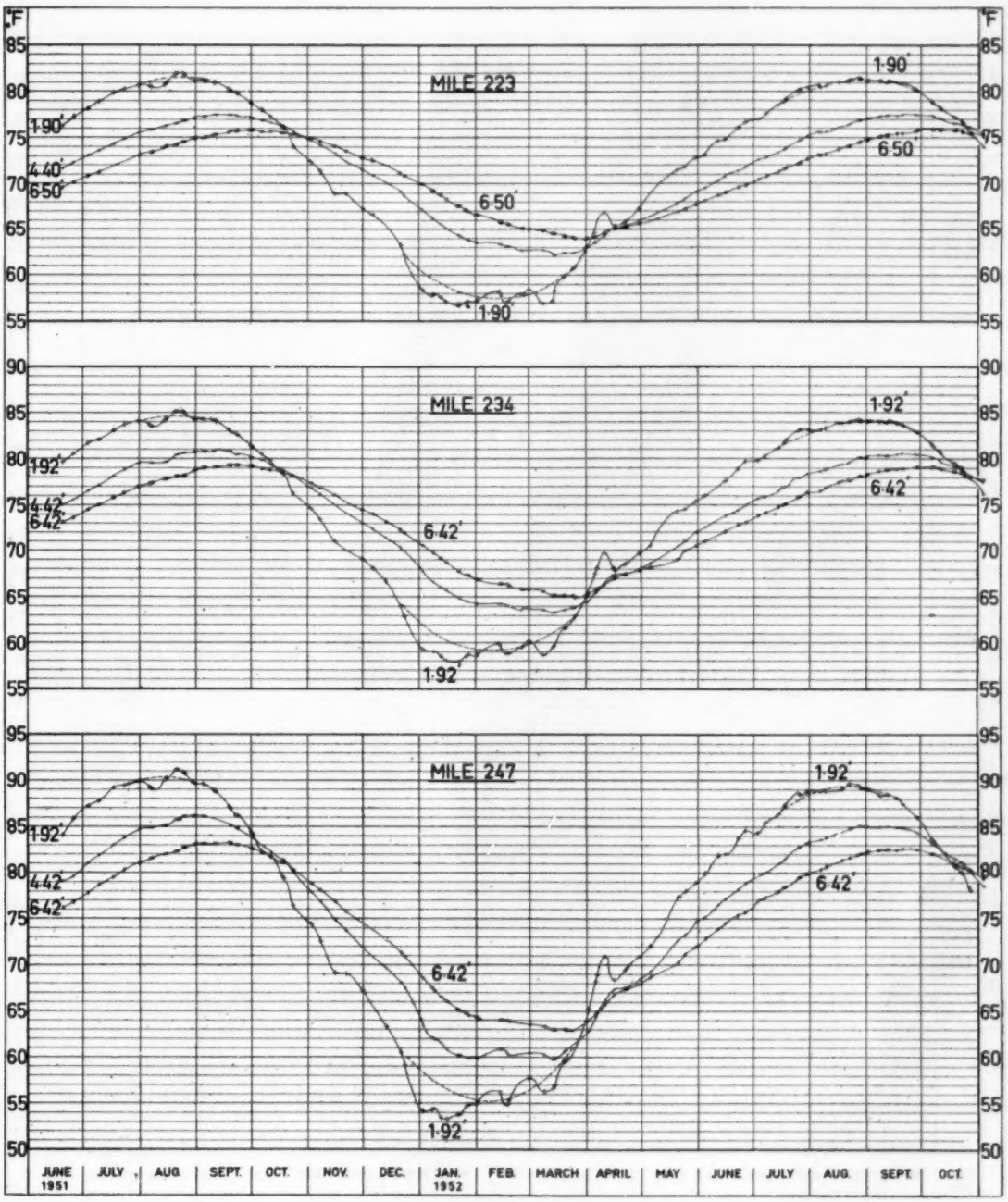
°F
MILE 223
1·90'
4·40'
6·50'
MILE 234
1·92'
4·42'
6·42'
MILE 247
JUNE 1951
JULY
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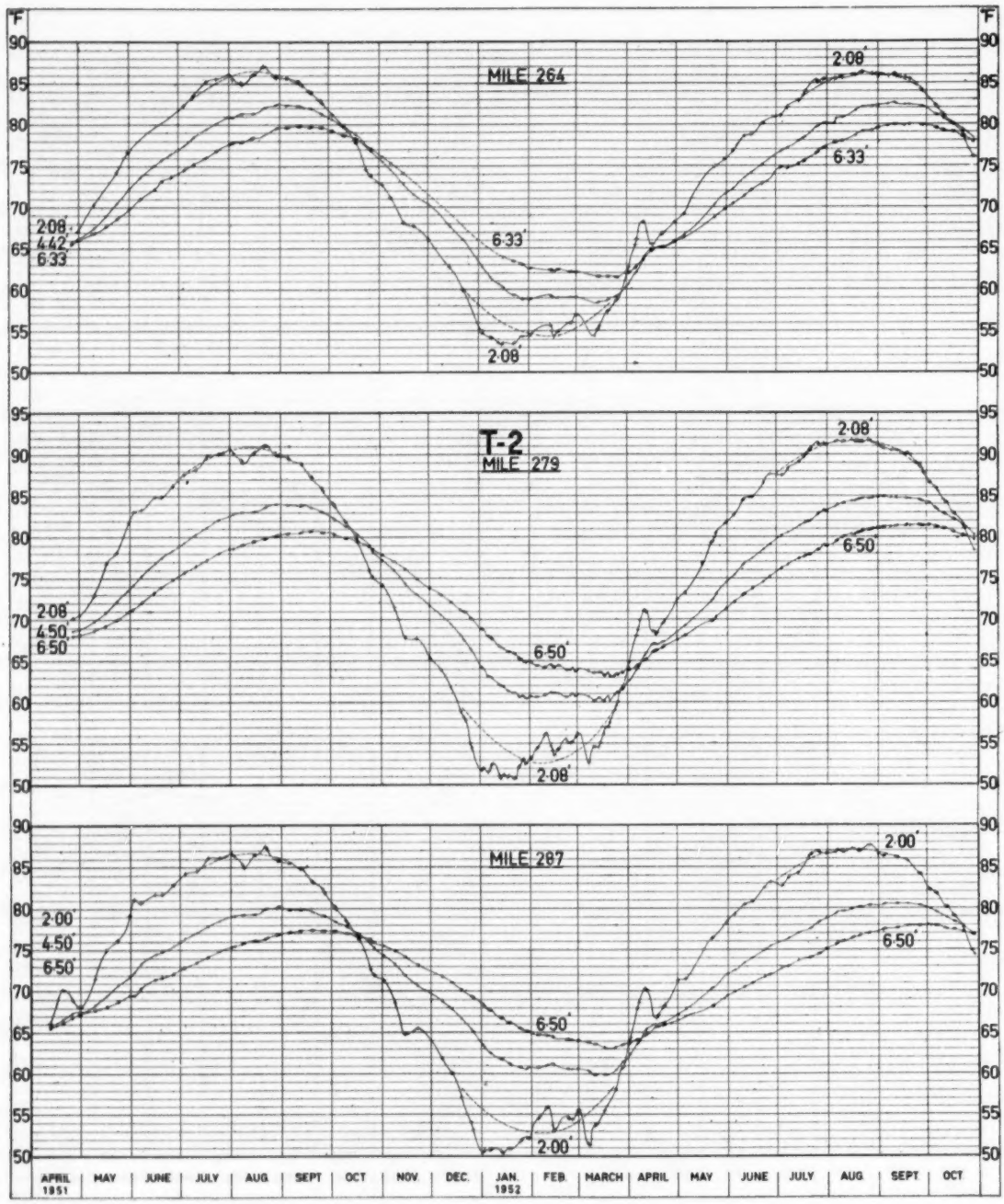
°F
MILE 264
2·08'
4·42'
6·33'
6·33'
2·08'
2·08'
6·33'
T-2
MILE 279
2·08'
4·50'
6·50'
6·50'
2·08'
2·08'
6·50'
MILE 287
2·00'
4·50'
6·50'
6·50'
2·00'
2·00'
6·50'
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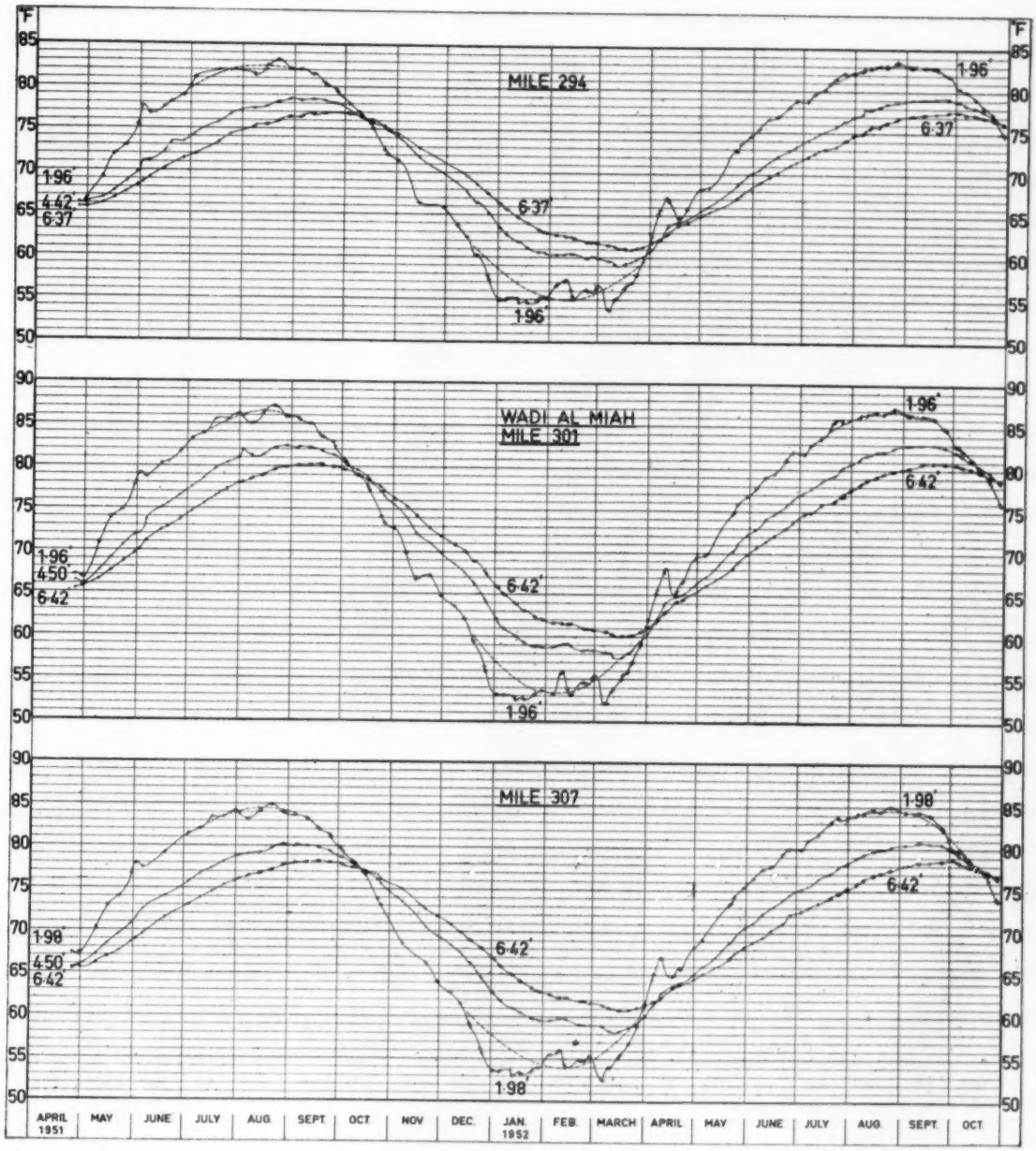
°F
MILE 294
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4·42'
6·37'
6·37'
1·96'
1·96'
6·37'
WADI AL MIAH
MILE 301
1·96'
4·50'
6·42'
6·42'
1·96'
1·96'
6·42'
MILE 307
1·98'
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6·42'
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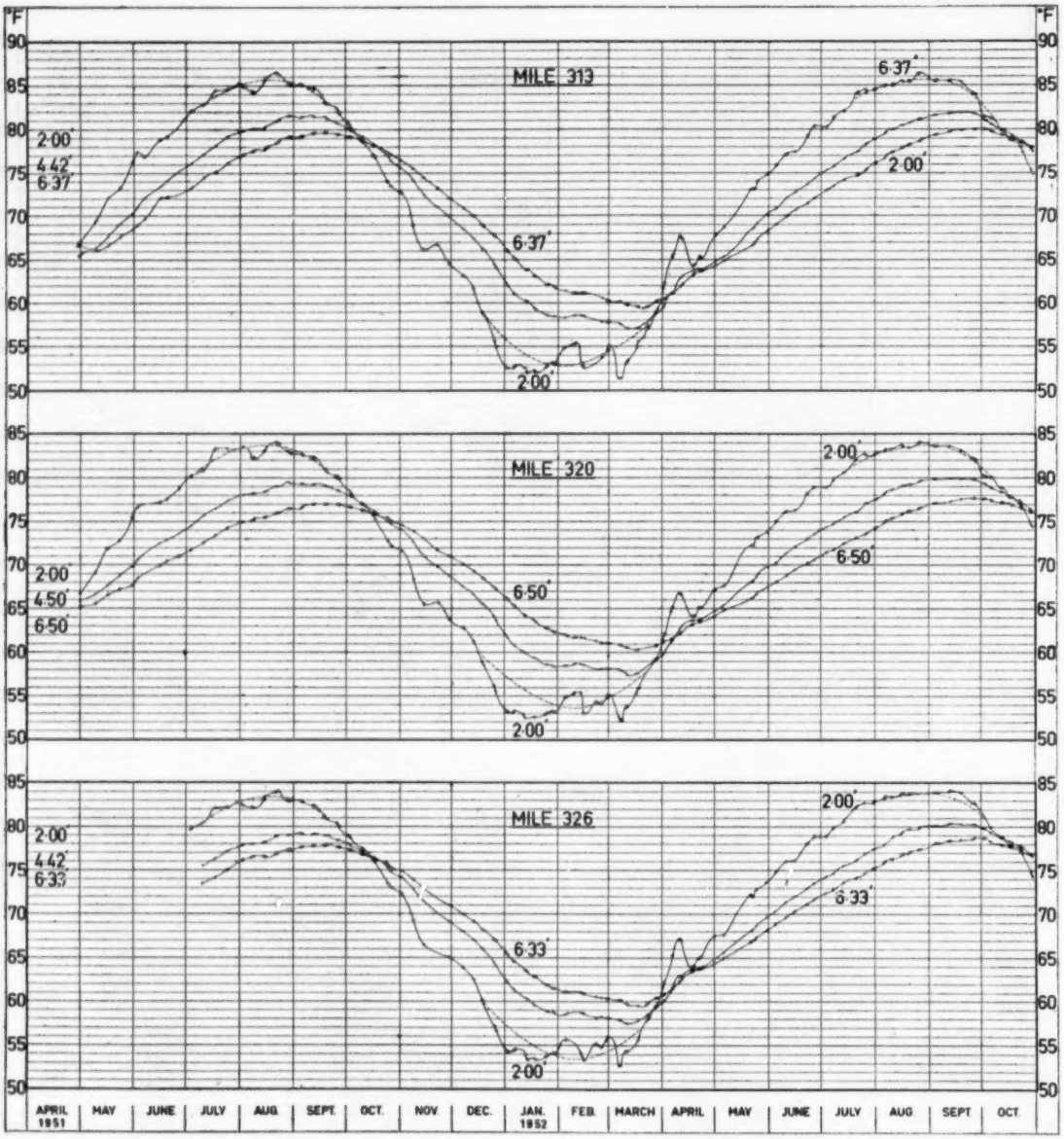
°F
MILE 313
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4·42'
6·37'
6·37'
2·00'
6·37'
2·00'
MILE 320
2·00'
4·50'
6·50'
6·50'
2·00'
2·00'
6·50'
MILE 326
2·00'
4·42'
6·33'
6·33'
2·00'
2·00'
6·33'
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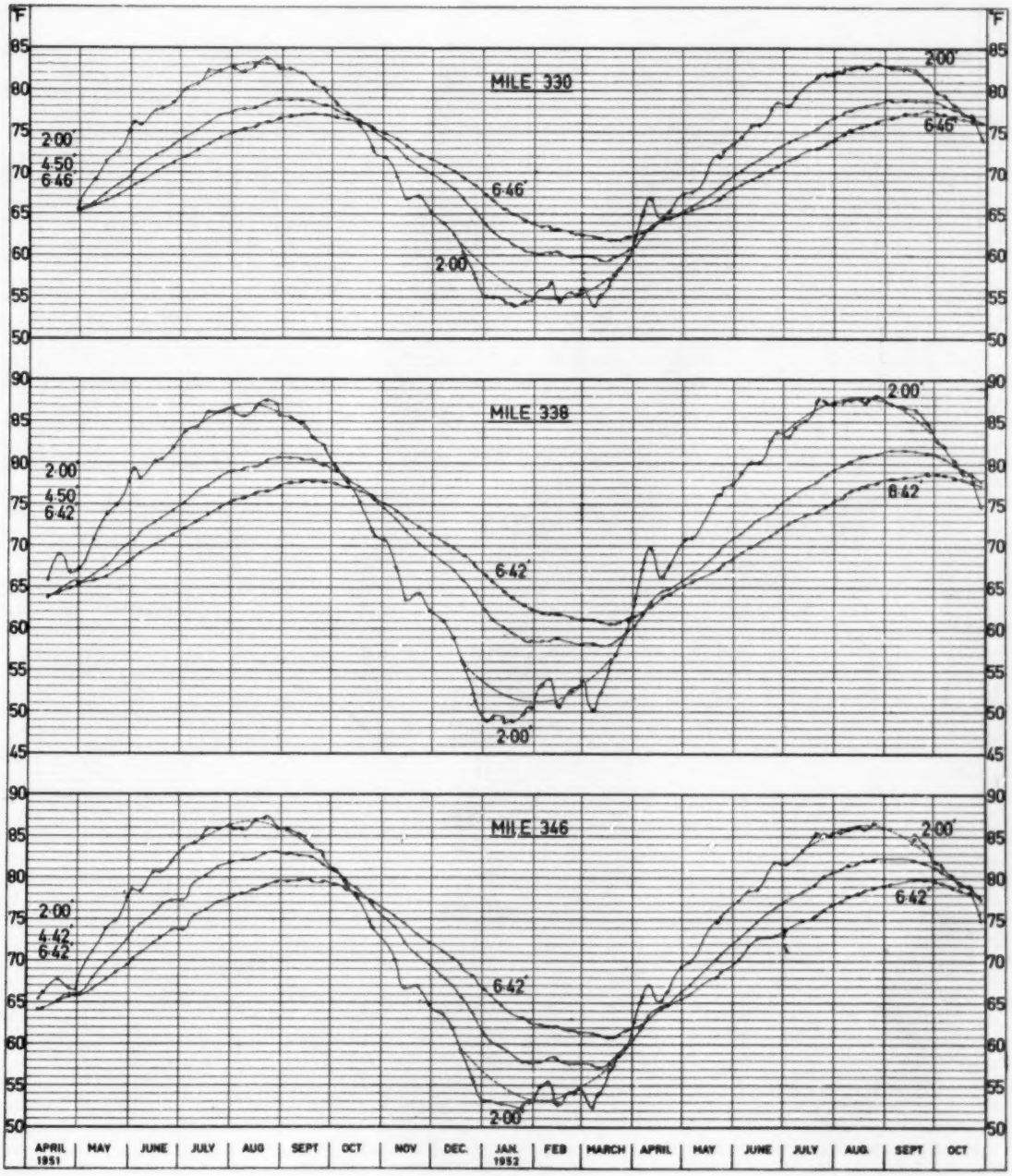
°F
MILE 330
2·00'
4·50'
6·46'
MILE 338
2·00'
4·50'
6·42'
MILE 346
2·00'
4·42'
6·42'
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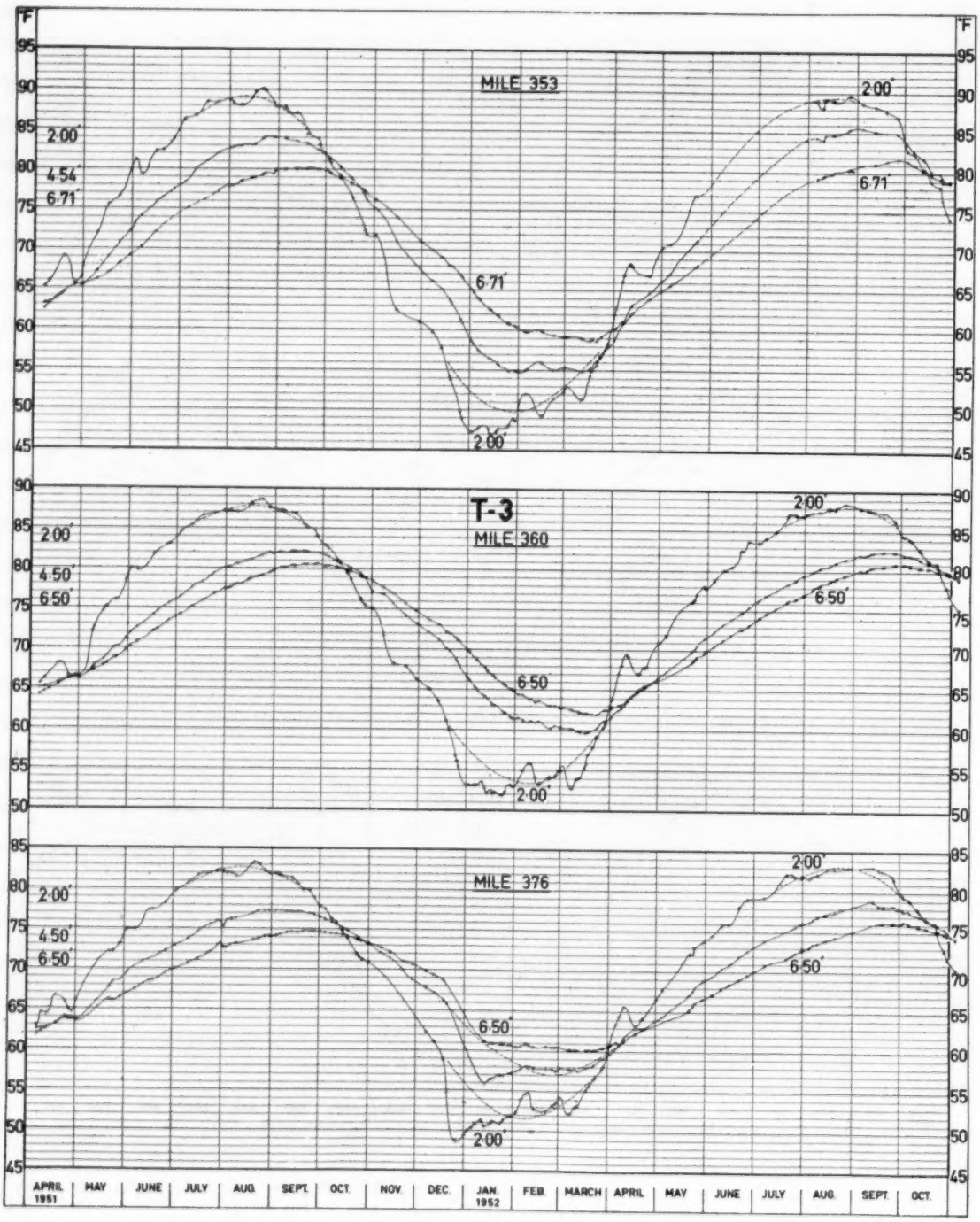
°F
MILE 353
2·00'
4·54'
6·71'
T-3
MILE 360
4·50'
6·50'
MILE 376
APRIL 1951
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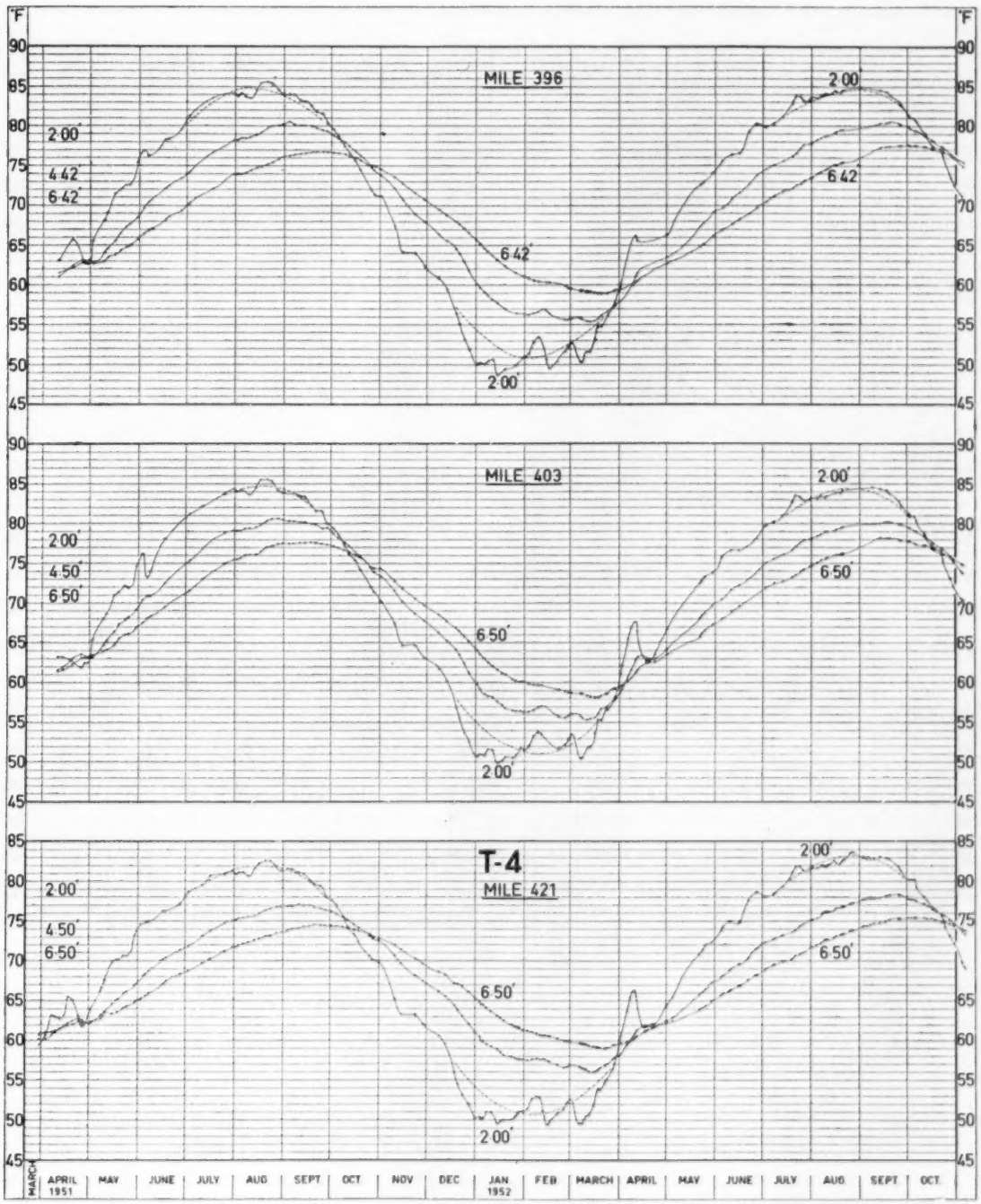
°F
MILE 396
2·00'
4·42'
6·42'
MILE 403
2·00'
4·50'
6·50'
T-4
MILE 421
2·00'
4·50'
6·50'
MARCH
APRIL 1951
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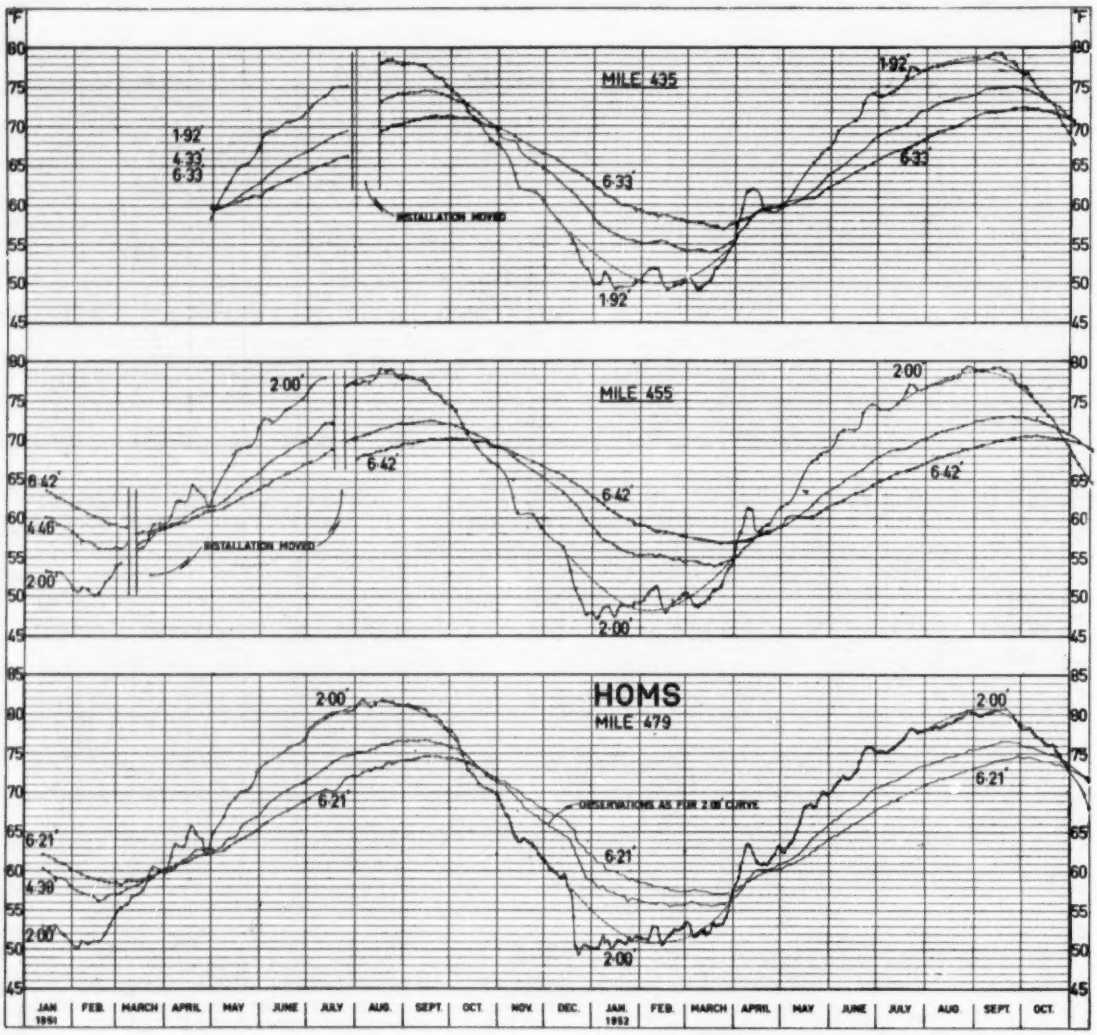
F
MILE 435
1·92'
4·33'
6·33'
INSTALLATION MOVED
MILE 455
2·00'
6·42'
4·46'
HOMS
MILE 479
6·21'
4·30'
OBSERVATIONS AS FOR 2 IN CURVE
JAN. 1951
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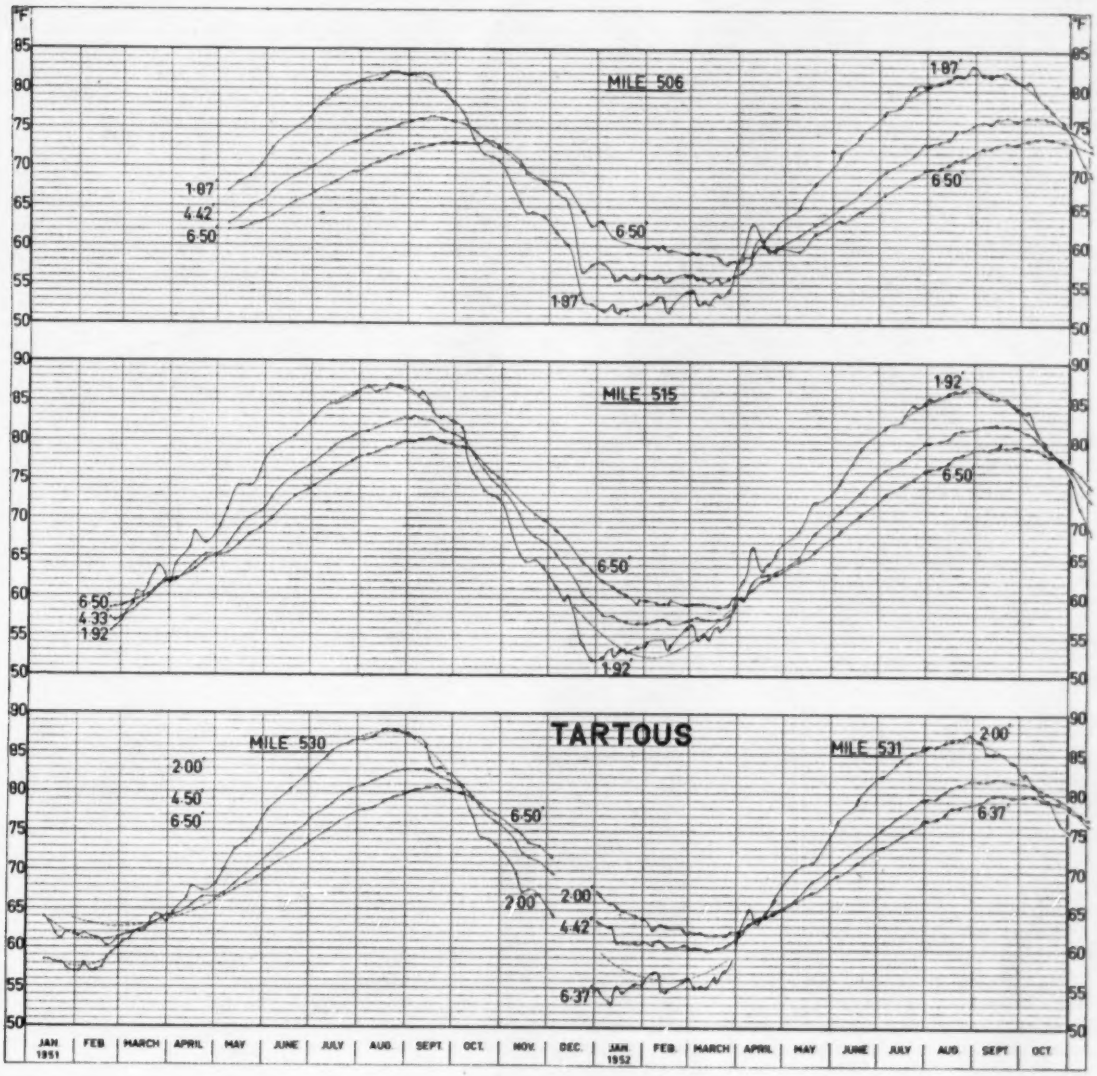
°F
MILE 506
1-07
4-42
6-50
6-50
1-07
1-07
6-50
MILE 515
6-50
4-33
1-92
6-50
1-92
1-92
6-50
TARTOUS
MILE 530
2-00
4-50
6-50
6-50
2-00
2-00
4-42
6-37
MILE 531
2-00
6-37
JAN 1951
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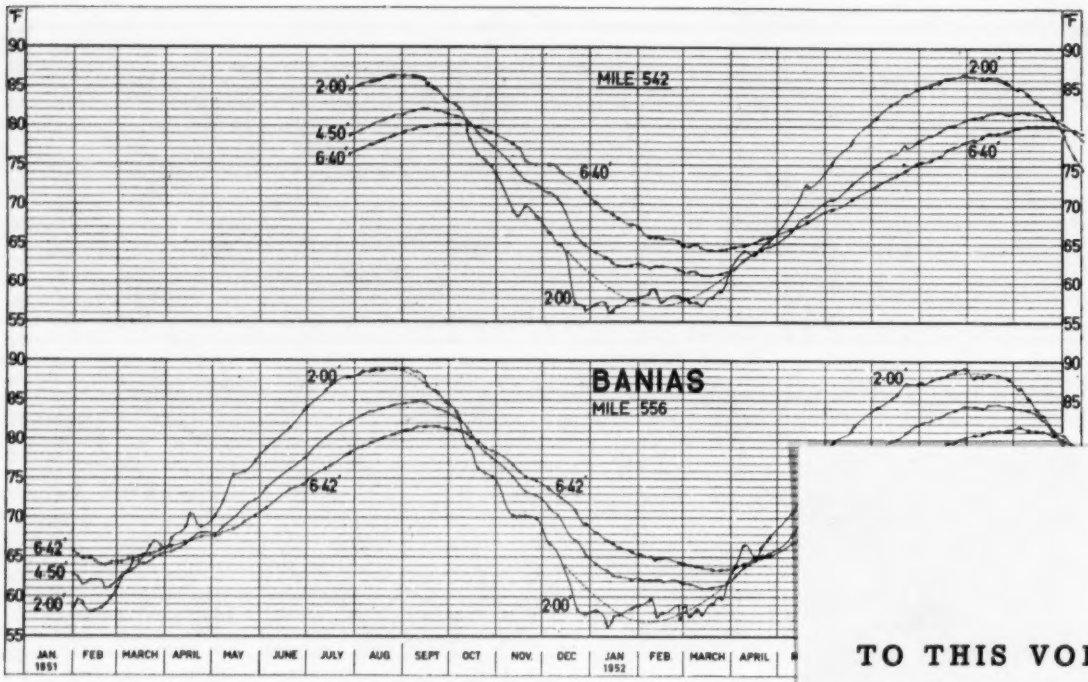

assumed reduction in the external radius of the pipe. Allowance must be made for increase in temperature in passing through pump stations arising from heating in the pumps or heat exchangers.

Comparison of Calculated and Observed Oil Temperatures

Fig 7 shows some examples of predicted and corresponding observed oil temperatures. It should be noted that the observed temperatures are approximate only. Oil temperatures vary appreciably and erratically consequent on changes in operating conditions. Heat pick-up in the stations varies irregularly, and sharp changes in temperature may occur whenever suction tanks are changed. In consequence, steady conditions are rarely established, and it becomes necessary to follow a slug of oil down the line from station to station to obtain reliable corresponding oil temperatures.

Comparison of Conductivities Derived from Temperature Curves and Oil Temperatures

In some few instances accurate oil temperatures are available for lengths of pipeline and for a few hours on a particular day. The results are shown in Table V, together with corresponding conductivity values derived from the soil temperature curves. It will be seen that fair agreement is obtained in this limited comparison.

T

Location			
Date			
Duration of test, hr			
Length of section, ft			
Pipe O.D., inches			
Initial oil temperature, °F			
Final oil temperature, °F			
Throughput, mil. lb/hr			
Hydraulic gradient, ft. hd/ft run			
Frictional heat, B.T.U/ft run/hr			
Heat capacity of flowing oil, B.T.U/lb/° F	0·456	0·452	0·445
Ground temperature at pipe depth, °F	62	62	61
Effective thermal conductivity, B.T.U/sq. ft/hr/1° F/ft	0·59	0·35	0·24
Conductivity for section derived from temperature curves	0·52	0·33	0·24

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ACKNOWLEDGMENTS

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References

[1] Beale, E. S. L., Hartley, A. C., van Dyck, W. J. D., and van Wyck, Dr. "The Science of Petroleum," Vol. 1, p. 740. London: Oxford University Press, 1938.
[2] Brummage, K. G. *J. Inst. Petrol.*, 1950, **36**, 575.
[3] Ingersoll, L. R., Zobell, O. J., and Ingersoll, H. C. "Heat Conduction," Ch. 5. London: McGraw-Hill Publishing Co., 1948.

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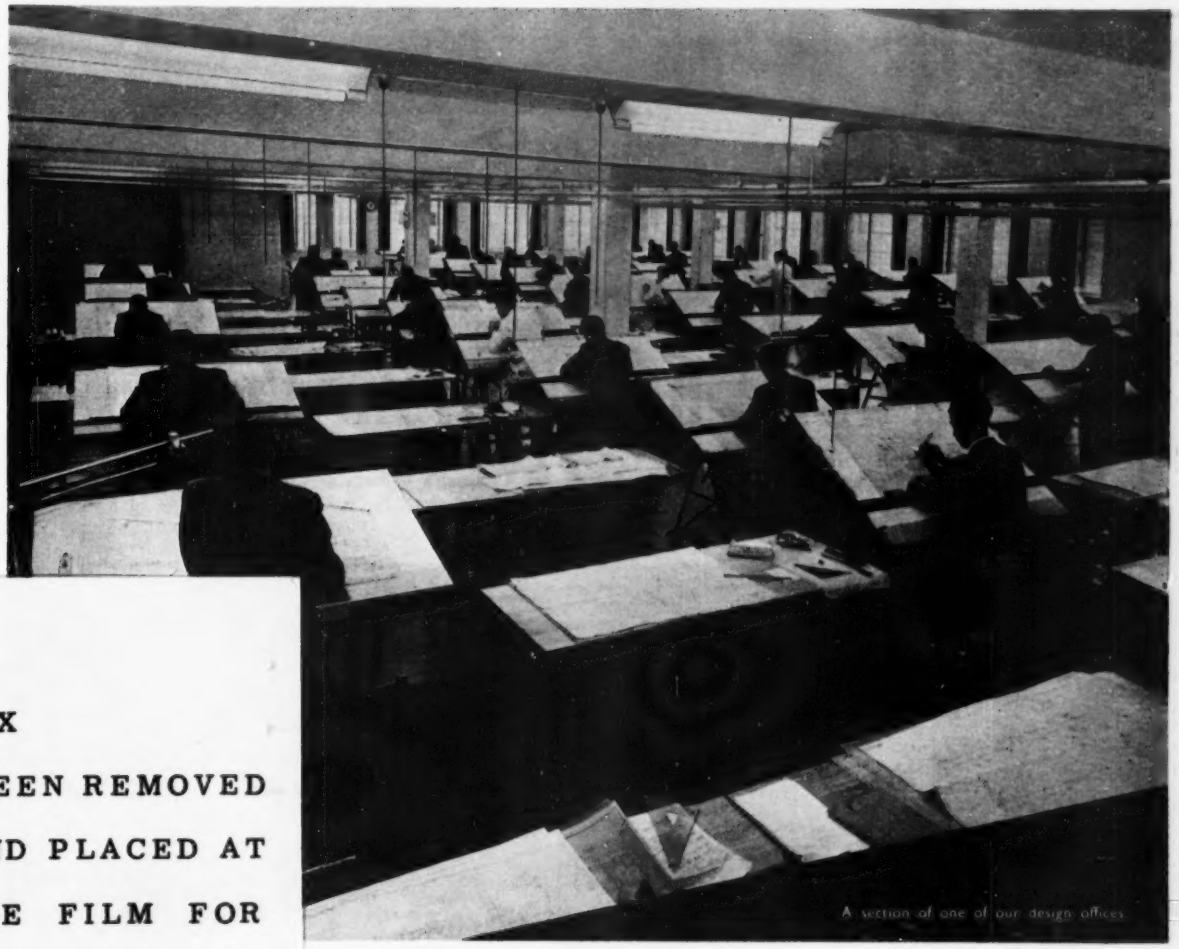
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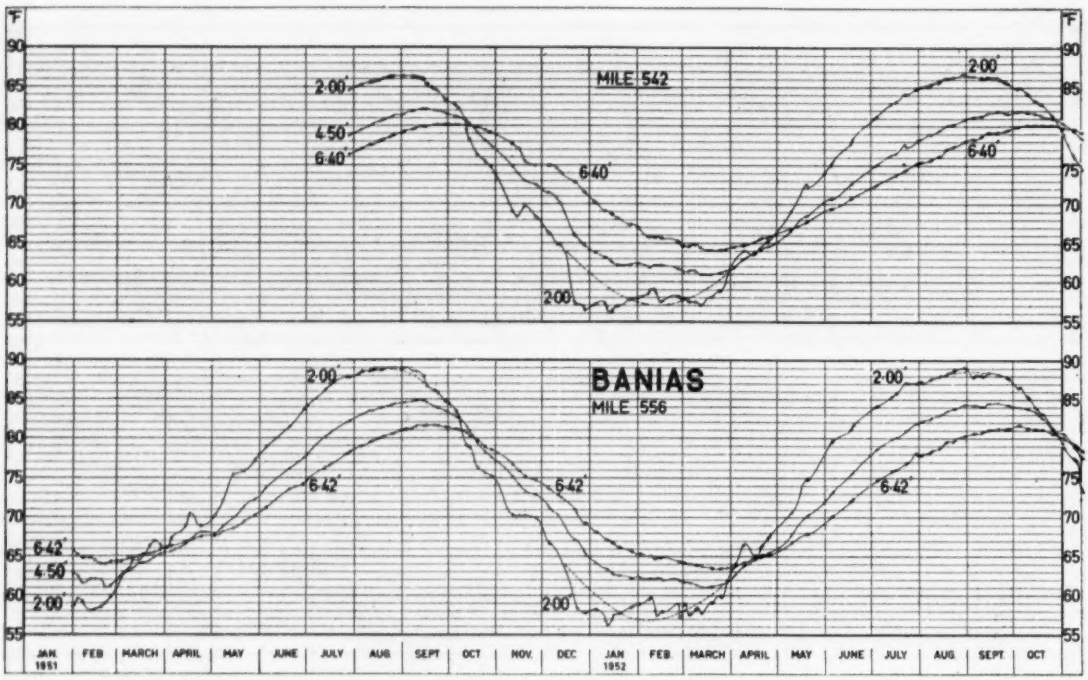

assumed reduction in the external radius of the pipe. Allowance must be made for increase in temperature in passing through pump stations arising from heating in the pumps or heat exchangers.

Comparison of Calculated and Observed Oil Temperatures

Fig 7 shows some examples of predicted and corresponding observed oil temperatures. It should be noted that the observed temperatures are approximate only. Oil temperatures vary appreciably and erratically consequent on changes in operating conditions. Heat pick-up in the stations varies irregularly, and sharp changes in temperature may occur whenever suction tanks are changed. In consequence, steady conditions are rarely established, and it becomes necessary to follow a slug of oil down the line from station to station to obtain reliable corresponding oil temperatures.

Comparison of Conductivities Derived from Temperature Curves and Oil Temperatures

In some few instances accurate oil temperatures are available for lengths of pipeline and for a few hours on a particular day. The results are shown in Table V, together with corresponding conductivity values derived from the soil temperature curves. It will be seen that fair agreement is obtained in this limited comparison.

TABLE V

Location	K-1–M-22	M-95–M-129	M-165–M-202
Date	19.1.53	2.2.53	19.2.53
Duration of test, hr	5	5	5
Length of section, ft	114,200	181,300	197,350
Pipe O.D., inches	30	32	32
Initial oil temperature, °F	108·0	99·6	84·1
Final oil temperature, °F	105·6	94·4	82·5
Throughput, mil. lb/hr	6·11	5·23	3·75
Hydraulic gradient, ft. hd/ft run	0·00456	0·000993	0·00136
Frictional heat, B.T.U/ft run/hr	35·7	4·13	6·57
Heat capacity of flowing oil, B.T.U/lb/°F	0·456	0·452	0·445
Ground temperature at pipe depth, °F	62	62	61
Effective thermal conductivity, B.T.U/sq. ft/hr/1° F/ft	0·59	0·35	0·24
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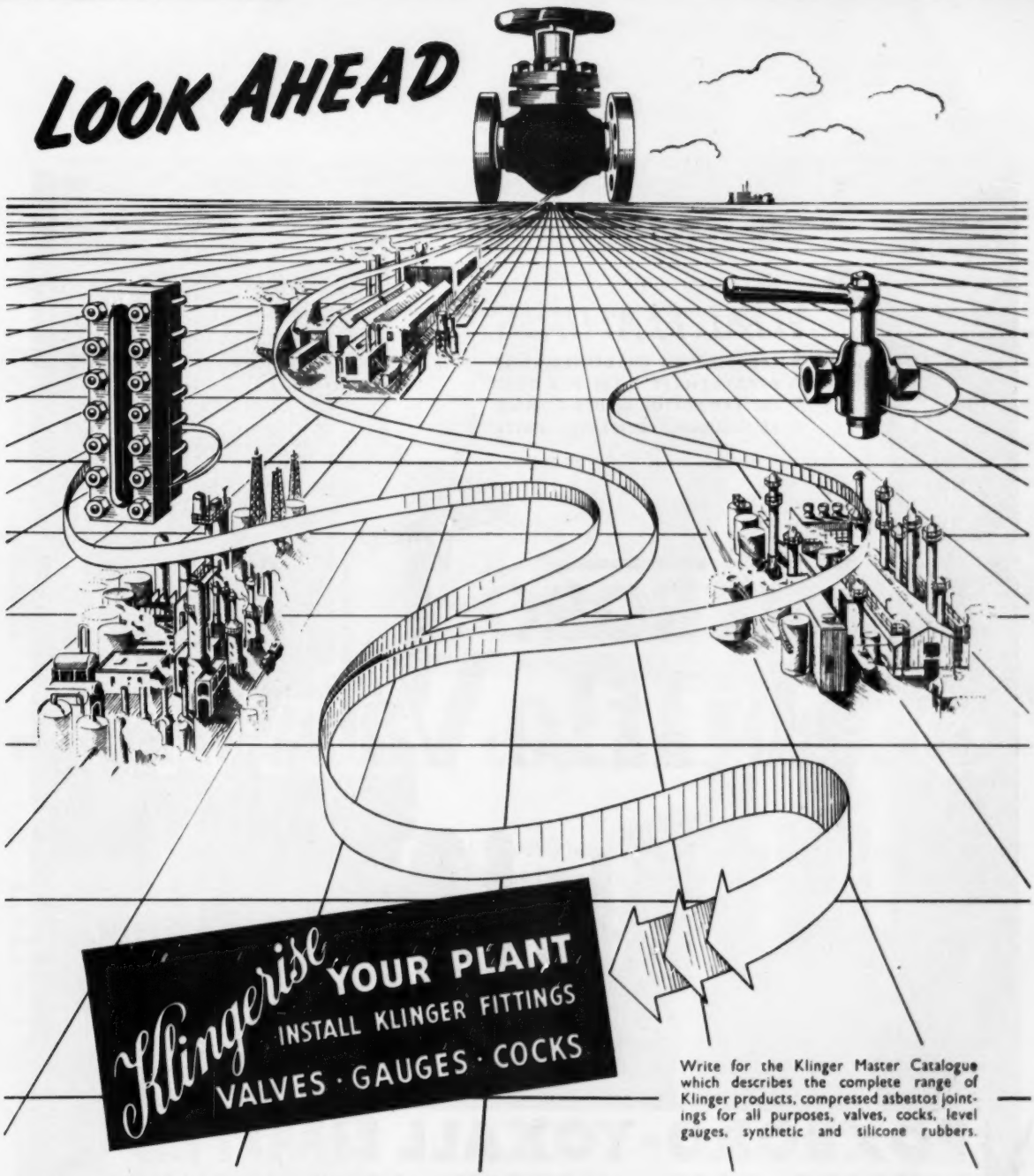

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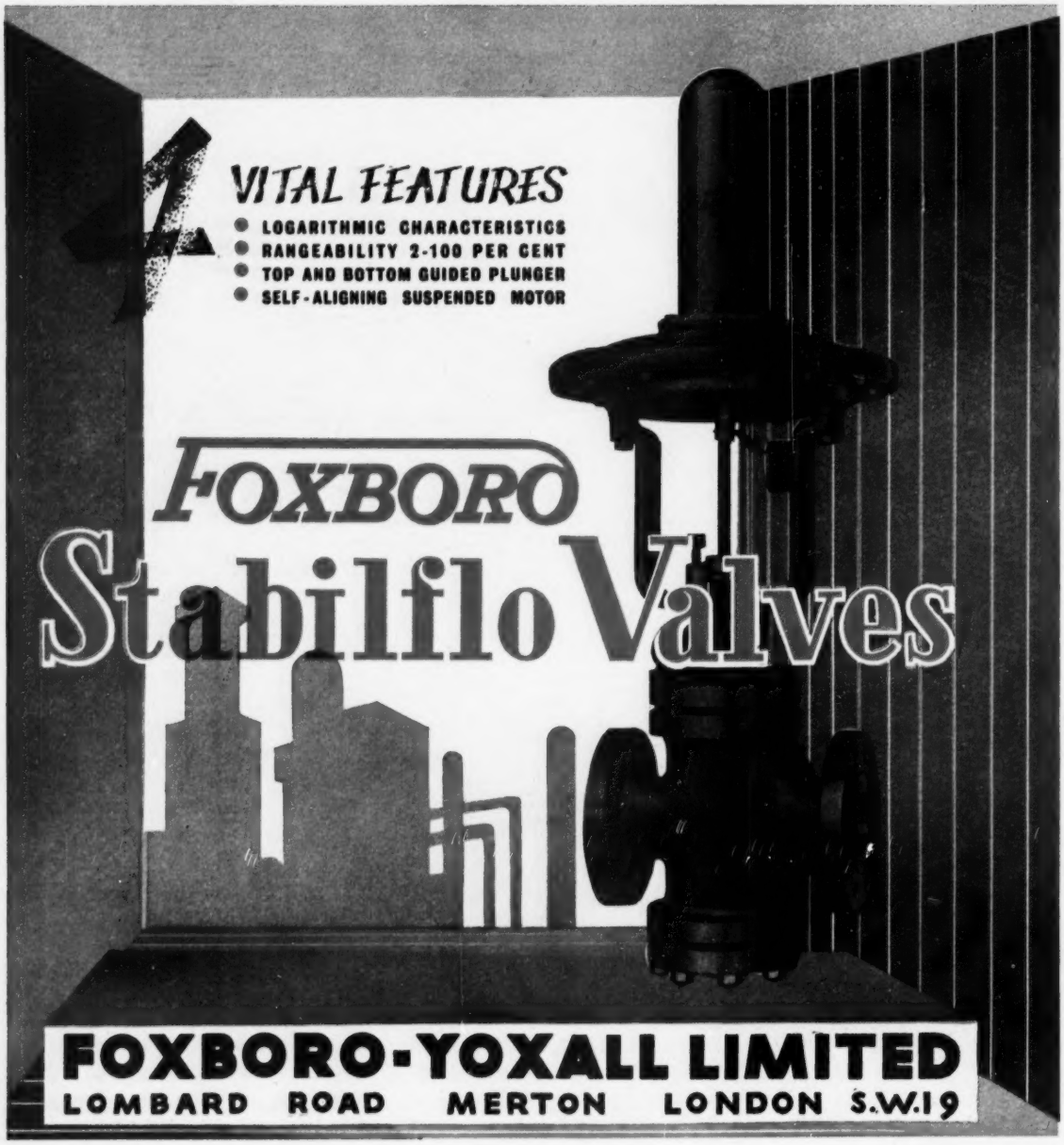
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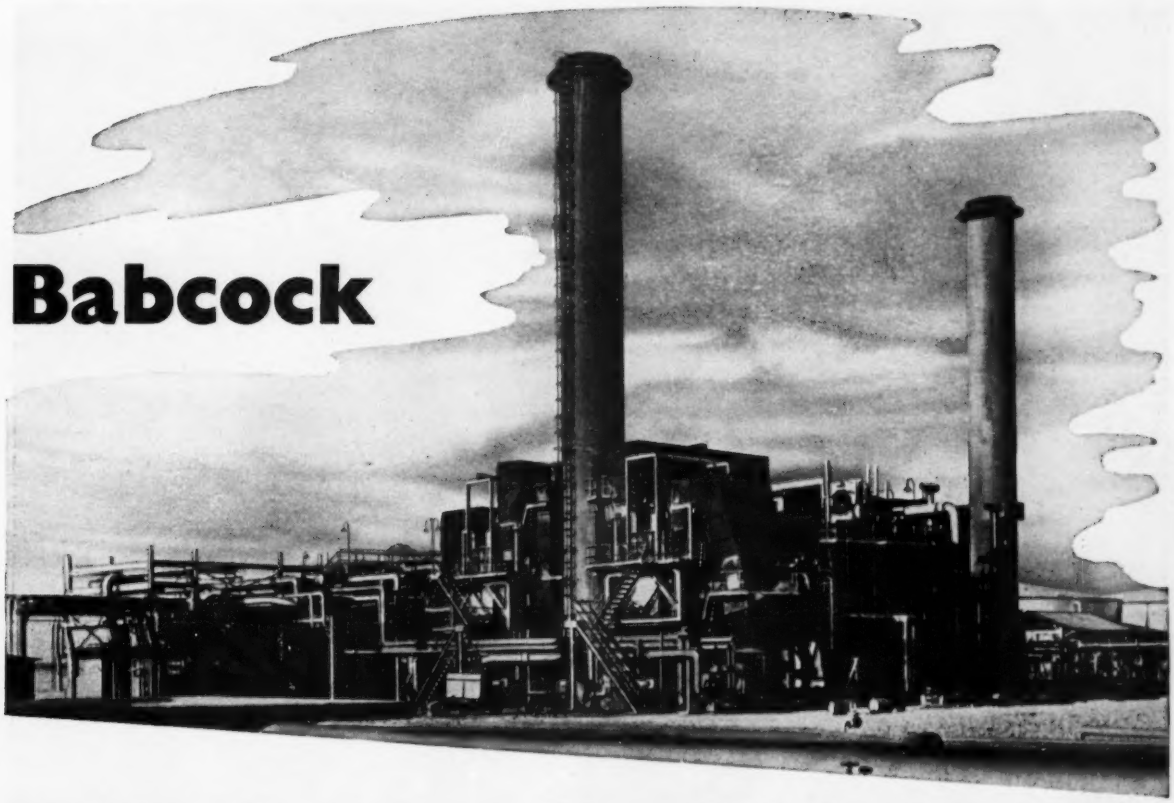

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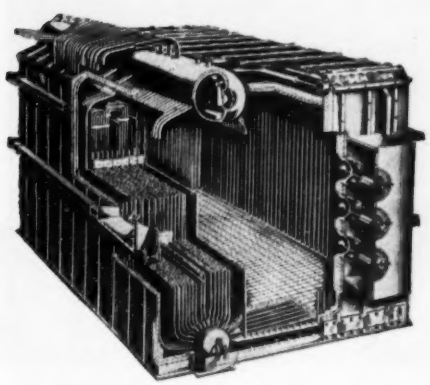
Below: *Sectional view of an oil-fired Babcock Integral Furnace boiler.*



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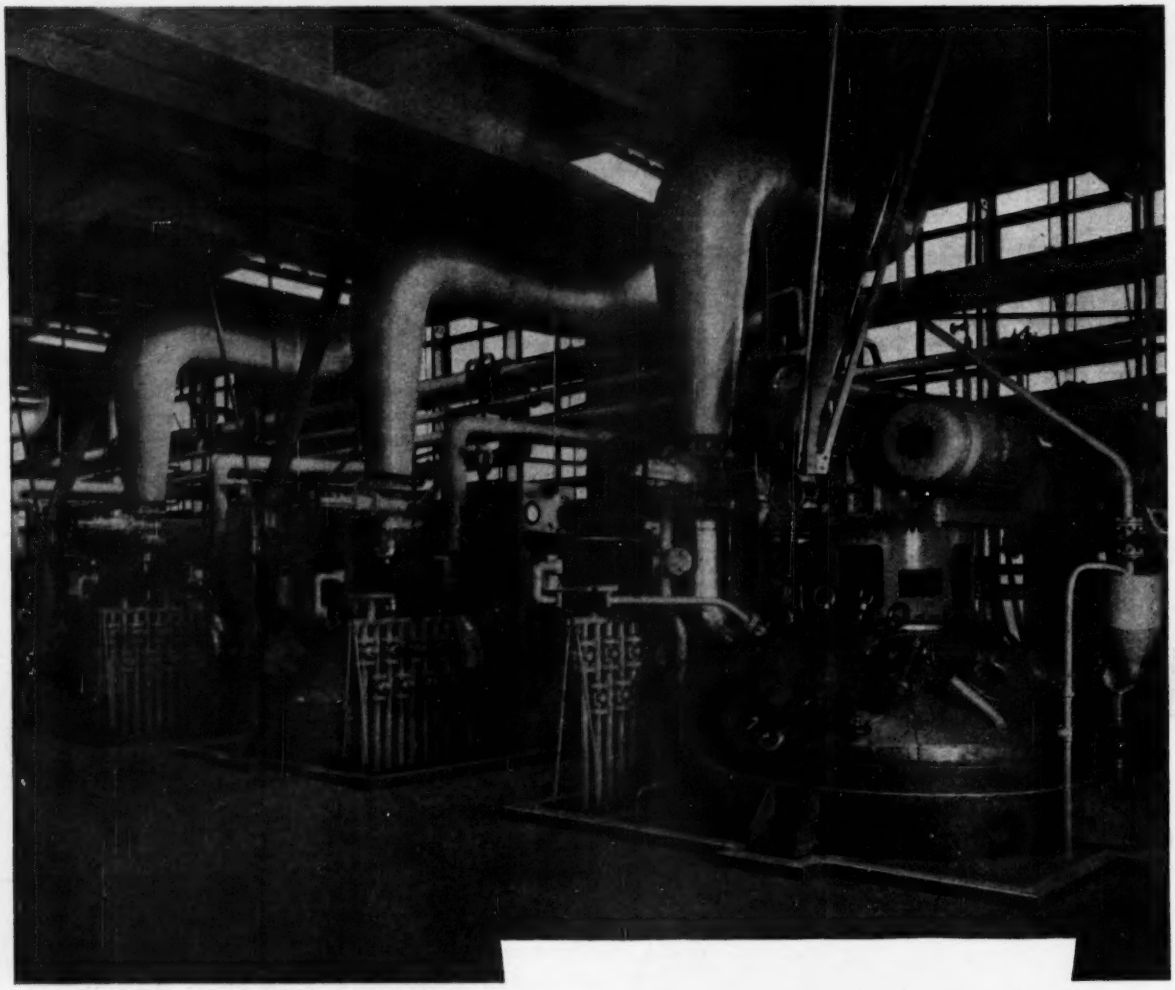

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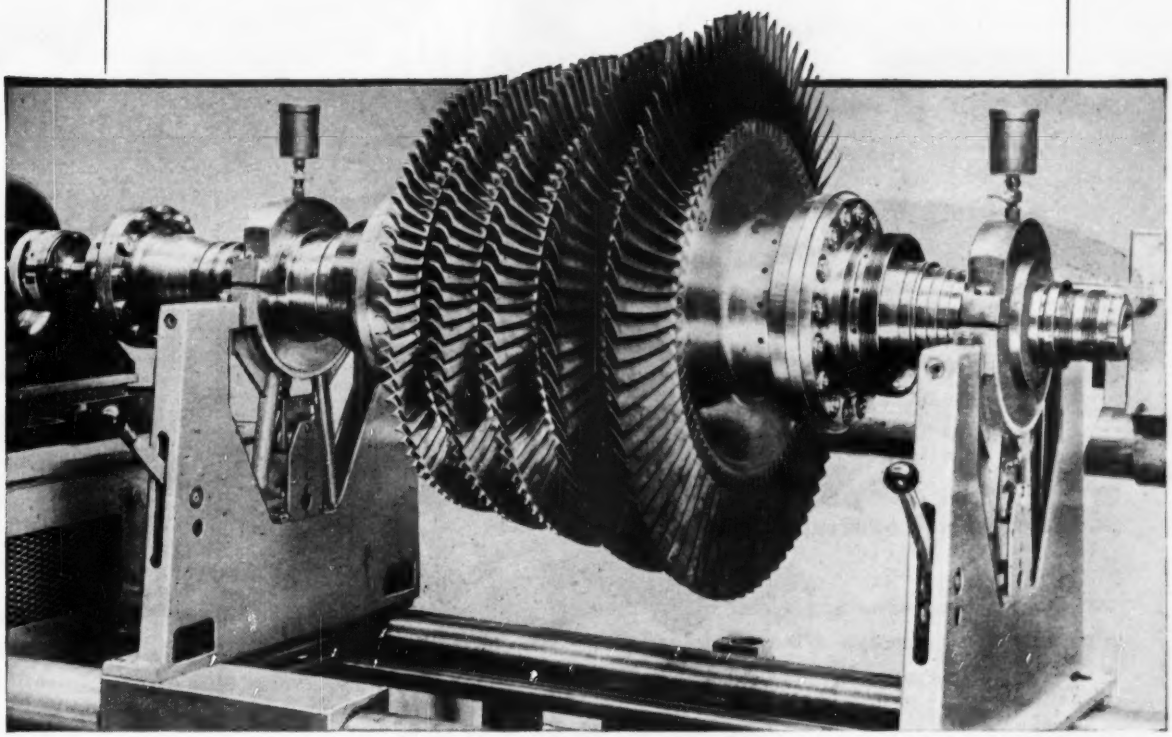

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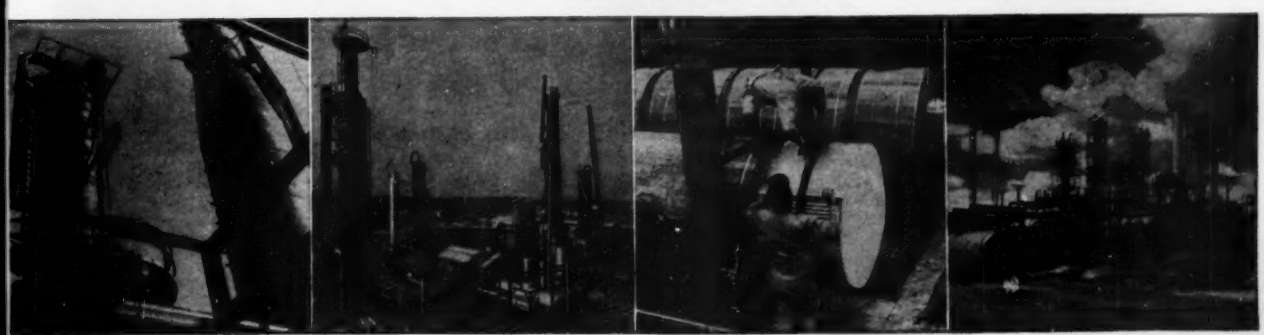

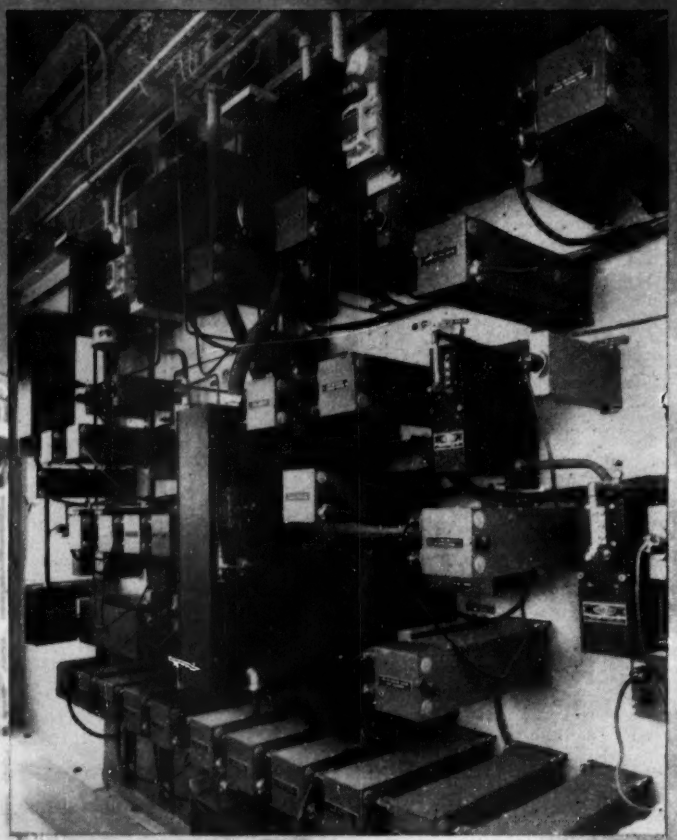

This view shows the back of the graphic control panel and of the electronic instruments for the UOP Platforming unit at the refinery of Rock Island Refining Corporation at Indianapolis, Ind. This Platformer is the first complete refinery unit in the United States to be controlled by electronic equipment.

Rock Island Refining Corp. Has First Complete Refinery Unit Controlled By Electronics

By L. E. Winkler
President
Rock Island Refining Corp., Indianapolis, Ind.

PROGRESSIVE thinking and action are vital to our refining operations. Since Rock Island Refining Corporation was organized in 1940, we have constantly sought to maintain our position as one of the most modern refineries in the world, dedicated to staying in the forefront of the petroleum refining industry as it produces higher quality products.

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Our decision to install electronic controls was based on economic factors as well as our desire to keep ahead of the industry in modern refining techniques. We took a long-range look at the potentials of this new type of equipment and ascertained that:

(1) It would increase the reliability of the Platformer's operation in cold weather by eliminating the possibility of freezing up of instrument transmission lines.

(2) It would do away with racks for the pneumatic tubing from the graphic panel to the battery area, thus reducing initial installation costs and problems connected with startup and maintenance operations.

(3) It would result in better control because of the increased sensitivity of electrical impulses.

Controls Work Perfectly

The electronic controls worked perfectly from the very beginning. On the day selected for the startup of the Platformer, oil was put into the unit at 9:30 a.m., and in less than three hours the unit was completely "lined out"—operating smoothly at the desired conditions. In less than two weeks, the unit had fully proved itself and had come to be considered a part of our routine refinery operations. Universal Oil Products Company designed, engineered and licensed the Platformer. UOP's instrument department engineered the installation of the electronic controls.

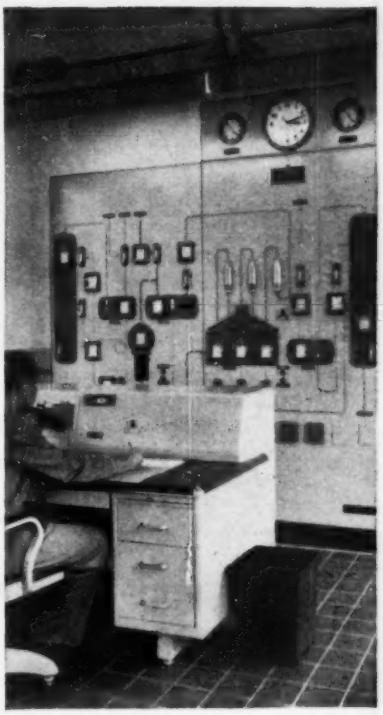
In our instrumentation, transmitters located in the battery area of the Platformer measure temperatures, pressures and flow and convert them to electrical signals. These go to recorders located on the graphic panel and to controllers, also located on the panel.

The controller compares the signals with a signal from the set point mechanism on the recorder that has been set previously by an operator. The controller sends out a current signal to the control valve, causing it to assume a given position. In the event the transmitter signal does not match the set point signal exactly, the controller modifies the current signal to the valve, located in the battery area. At the valve, the current signal is converted to a pneumatic pressure corresponding to the current signal in order to supply the power necessary to position the valve. This causes the valve to either open slightly or close slightly in order to bring the transmitter signal back into line with the set point signal.

Electronic Controls Act Swiftly

We have found that the electronic controls give almost instantaneous response when there are variations in temperature, pressure or flow through the Platforming unit. In addition, there are few moving parts in the equipment, thus reducing maintenance and wear. There is also complete interchangeability of parts, making it as easy to change parts as it is to change a light bulb.

We at Rock Island are proud to be the first refinery in the United States to install complete electronic controls to operate a major processing unit, and we believe sincerely that this instrumentation will go far toward helping us to consistently make better petroleum products from the crude oil that we process.



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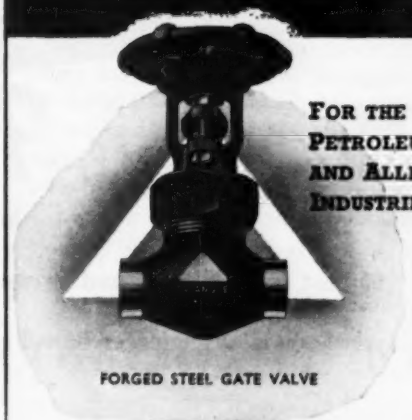

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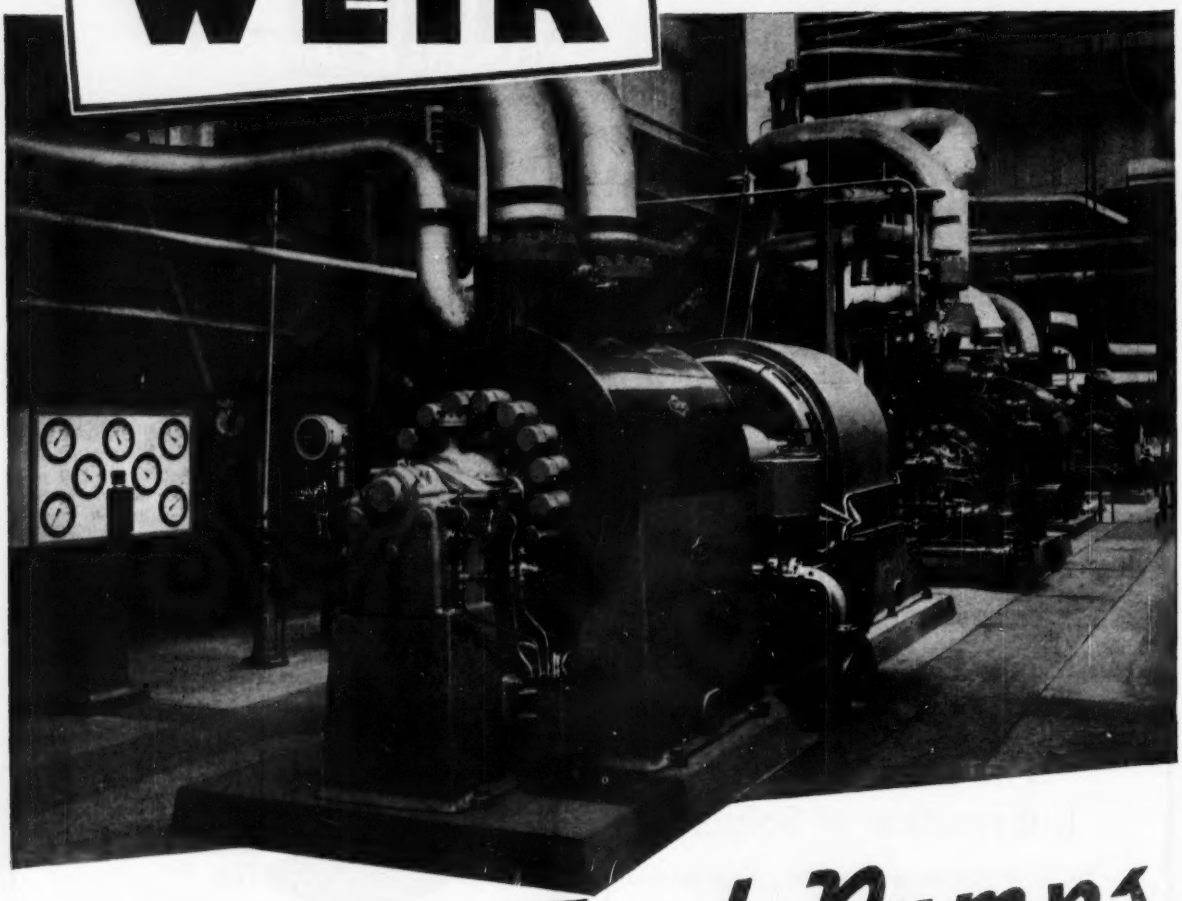

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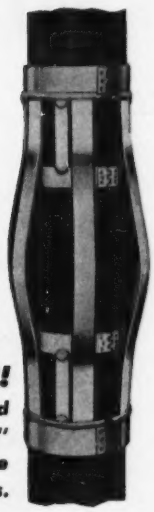

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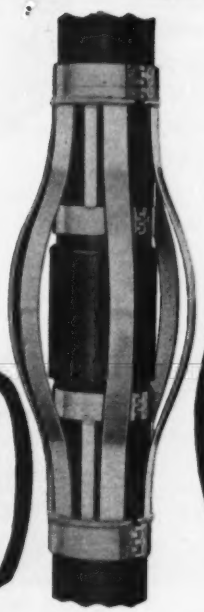

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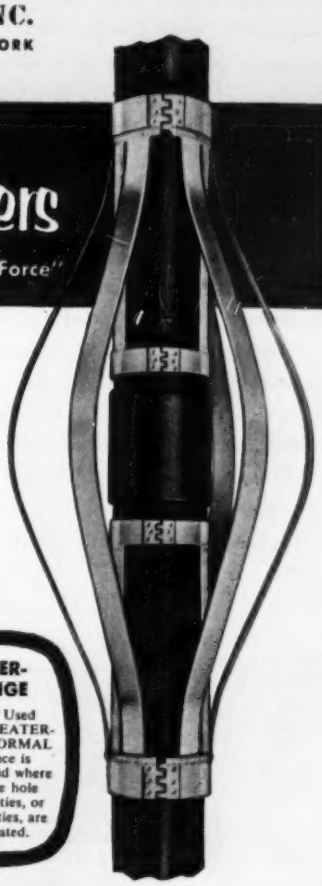

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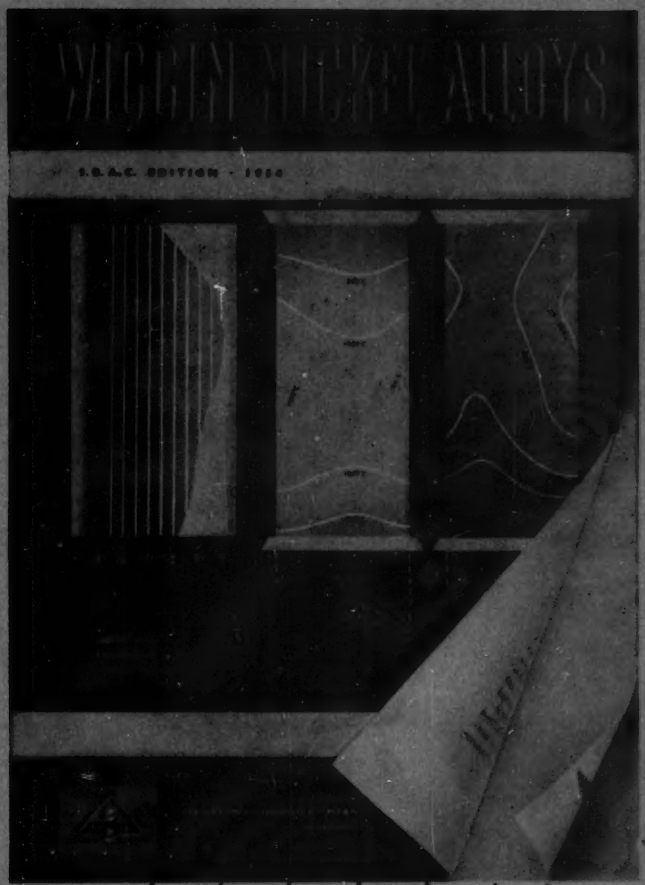

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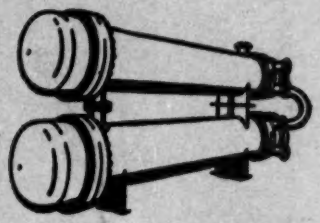

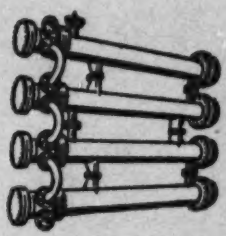

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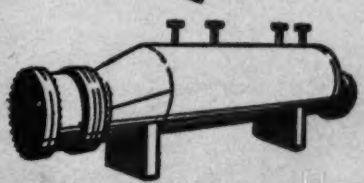

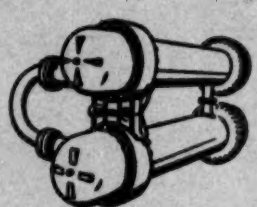

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